S. KUMAR

The Story of GLASS

National Council of
Educational Research and Training

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FOREWORD

During the last decade, the National Council of Educational Research and Training has been preparing supplementary readers in Science for school students. The aim is to stimulate the interest of school children in the world of Science and help them to keep in touch with the significant developments that are taking place in the various fields of Science.

"The Story of Glass", the latest book in the series, should be of interest not only to secondary school students but also to all those who use beautiful glassware and have been moved by the delicate beauty and transparent purity of such artistic creations of glass as a stained glass window or a richly engraved vase This book will provide both groups of readers a solid background of basic scientific knowledge about glass—its composition and properties, the different processes used from the earliest times to the present day in its manufacture, the role that it has played in the various branches of science and industry and the phenomenal achievements in science which have made possible the use of glass in space craft and laser communication.

Dr. S. Kumar, a distinguished scientist in the field of glass technology, has presented his subject in a most readable form. The Council is most grateful to Dr. Kumar for preparing this excellent book It is hoped that it will be found interesting and useful by students and other readers.

SHIB K MITRA
Director
National Council of
Educational Research and Training

PREFACE

"The Story of Glass" was written primarily with two types of readers in view, the higher secondary students in the Science stream and the general readers, who are interested to know the basic facts about glass, the methods of production, behaviour and applications in various fields.

Glass is being produced since the dawn of history In the first chapter a general overview has been presented of the development of glass technology with the growth of material civilization The subsequent chapter deals with the various methods currently being employed for the manufacture of various items of glass. This is followed by a presentation of the optical and mechanical behaviour and uses of glass in relation to these two important properties. The last chapter is mostly devoted to newer developments in this field. Throughout the book, the basic theme has been the role of glass in the overall scheme of material progress

Applications of glass are numerous and varied, and each is linked with certain concepts of physics or chemistry. Although each of the topics has been developed *ab initio*, it has been assumed that the reader possesses an adequate background in the relevant field of basic science Some of the subjects, particularly in the last chapter, are somewhat involved and considering the scope and intended size of the book, the treatment has been kept brief and sketchy The readers who may feel that there is more to be known may refer to the books listed in the Appendix

Since the time the manuscript was prepared, certain significant developments have taken place, particularly in the fields of fibre glass composites and optical communication through fibre glass It is hoped that

in a subsequent edition it will be possible to update the Reader in some of these respects.

During the preparation of the manuscript, the author has drawn materials from various standard books and papers. He is grateful to Shri K D Sharma, Director, Central Glass and Ceramic Research Institute for his kind support and permission to publish many of the photographs He also records his gratitude to the late S.N Saha and Shri R Bhattacharya for preparation of most of the illustrations and to prominent glass manufacturers who had kindly supplied some of the photographs Sincere thanks are also due to the National Council of Educational Research and Training and, particularly, to Shri K J Khurana, for his ungrudging help in bringing out this volume

S Kumar
Deputy Director
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The Early Story

MATTER is generally known to exist in three states, namely, gaseous, liquid and solid. In a gas, atoms or molecules knock around at velocities that decrease with decreasing temperature till a point is reached at which it condenses to the liquid state. On further cooling, the liquid is transformed into a crystalline solid in which the constituent units are arranged in a certain symmetrical order. There are, however, some liquid compositions which can be cooled through the crystallisation temperature without showing any marked tendency to form crystals. When sufficiently supercooled, such a liquid is transformed into a transparent and brittle

mass which is known as glass. For instance, if a hot sugar syrup is cooled it gets thicker and finally sets into a rigid mass. Without sugar in it, water alone cools to form ice, which is crystalline, whereas the candy made of syrup is glass. Glass is, therefore, neither a true liquid nor a crystalline solid—it is a different state of matter. A variety of liquid compositions can be super-cooled to the glassy state. Organic plastic materials, shellac, solutions of gelatin or sugar in water, etc. are some of the typical glass-forming substances.

The common glass that we see and use in our daily life is an inorganic product of fusion. Composition of the fused mass is so chosen that it can be cooled without crystallisation to form a clear, rigid glass. The primary ingredients of common glass are sand, limestone and soda. The raw materials of suitable quality are mixed in appropriate proportions and are fed into an almost white hot furnace. The roaring flames that sweep across the furnace melt the mixture to a syrupy liquid. The molten mass is allowed to remain in the furnace for a sufficient length of time to let the entrapped air and gases escape and then the refined glass flows into a cooler part of the furnace There it is allowed to cool to a sufficiently thick consistency so that it can be worked into different forms. It can be sucked or fed in the form of 'gobs' into machines for making containers or it can be drawn in the form of a continuous sheet or rolled between iron rollers to form a long flat plate of glass.

For the present, we do not propose to go into the modern technology of glass formation or the science of the glassy state of matter. Here, we shall briefly discuss the story of glass that has been made through the ages for common utility and aesthetic satisfaction of man.

BEGINNING OF THE BEGINNING

FIGURE 1.1 *Natural Glass (Obsidian)*

The beginning of this story dates back to the time when our planet, the earth, was in the process of taking its present form. The first glass was formed by the fusion of silica in the blazing fire (that had built the continents) and the natural glass thus formed was heaved onto the surface of the earth by volcanic action. This hard and brittle mass, called obsidian, can be found in different parts of the earth (Fig 1.1); there is, in fact, a whole mountain of obsidian in Yellow Stone National Park in the United States. Natural glass is heavily coloured and almost translucent in appearance due to the presence of impurities and can easily be chipped into long sharp pieces. Prehistoric men—the cave dwellers—must have wondered at this shiny and sharp material and found it suitable for making weapons and other primitive implements. Later, they discovered that this glass can be cut, shaped and curved to form jewellery, mirrors and even ceremonial masks. Glass was used by man even 25,000 years ago.

A new era began some 7,000 years ago when man found the method for making glass by himself. We do not know exactly how this discovery was made. In the last century B.C., the Roman historian Pliny wrote that some Phoenecian traders had moored their ship on the banks of the Syrian tidal river Belus. To prepare their dinner they placed their cooking pot on two blocks of soda or nitre, which they were carrying in the ship. The heat of the

cooking fire melted the soda and the molten material then reacted with the sand on the beach to form a pool of shining material. This was glass—the first glass that man had made. Be that as it may, it is generally accepted that the method of melting glass was discovered around 5,000 B C in Egypt or Mesopotamia probably by some potters when they were firing their pots. The glass thus formed was actually only a thin shiny glaze on the surface of the earthenware. Later it was discovered that if the glaze produced by fusion of sand and minerals could be made thick enough it would stand by itself. The first articles of glass were probably the solid glass beads made by this process in ancient times.

EGYPT, ROME AND THE BLOW PIPE

In ancient Egypt it was the custom to bury with a dead man precious presents, which included, among many other things, articles of glass. This social custom, and the comparatively dry climatic conditions in the country have been responsible for the excellent preservation of these articles of antiquity, which are now being discovered by modern archaeologists. Careful studies of these articles reveal that in the ancient city of Tel-el-Amarna, in Egypt, there existed a thriving glass industry during the reign of Amenhotep IV (1400 B C).

The process of making hollow glass containers was probably developed around this period in Egypt or in Mesopotamia which was conquered by the Egyptians in the fifteenth century B C They would first form a core of sand or clay of the desired shape and then build layers of glass on the core probably by repeated immersion of it into molten glass, till a sufficiently thick wall of glass was formed on the surface of the core. It was then cooled and the core was removed leaving the hollow container of glass. This

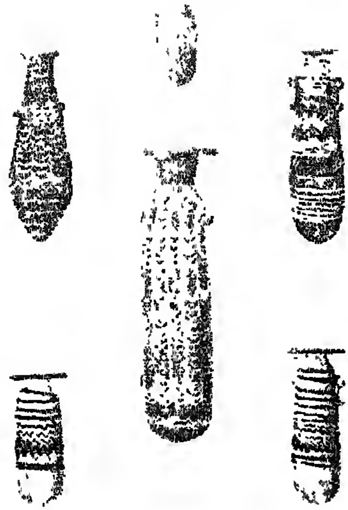


FIGURE 1.2 *Egptian Glass Vessels, probably produced by the Core-mould Process*

method is known as the "core-mould process". The articles produced by this process were variously coloured and sometimes almost translucent with a bright glistening surface resembling that of a precious stone. These crude shapes were highly valued and were the prized possessions of kings, priests and the nobility. For centuries the glass industry flourished in Egypt producing coloured beads, decorated hollow wares, etc. Figure 1.2 shows some of the typical Egyptian glass articles believed to have been produced by the core-mould process. From Egypt, Phoenecian traders carried this art to some of the other Mediterranean countries.

Around 300 B.C. a simple and yet revolutionary event took place when it was discovered that a hot pasty blob of glass gathered on a hollow iron tube could be blown with a puff of the mouth; the hot globe of glass thus formed could be manipulated into different forms or blown into various shapes It could also be blown in moulds of different forms. The use of a blow pipe in a glass factory of olden days is shown in Fig. 1.3. The second man on the right is seen gathering glass from a melting pot with a blow pipe. The third worker is blowing a bulb out of hot and soft glass and the next one is putting the blown ware in a hot chamber. It is apparent that in contrast to the older core-mould process, this

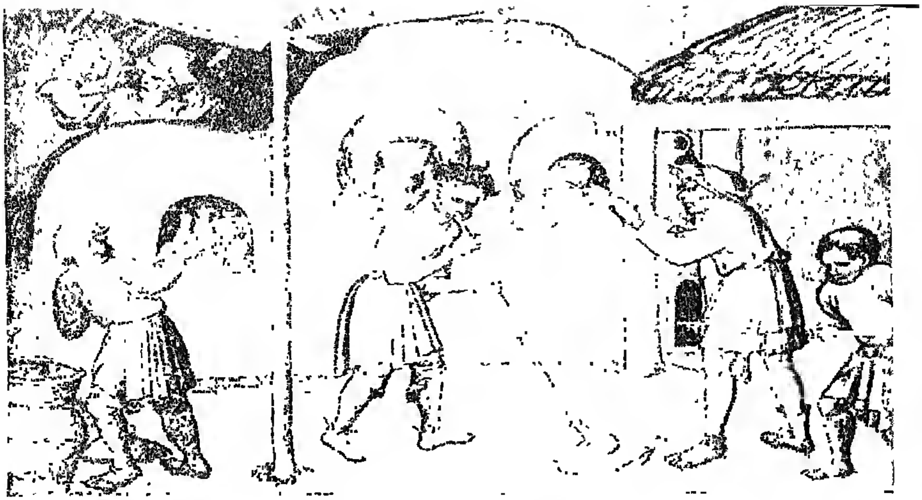
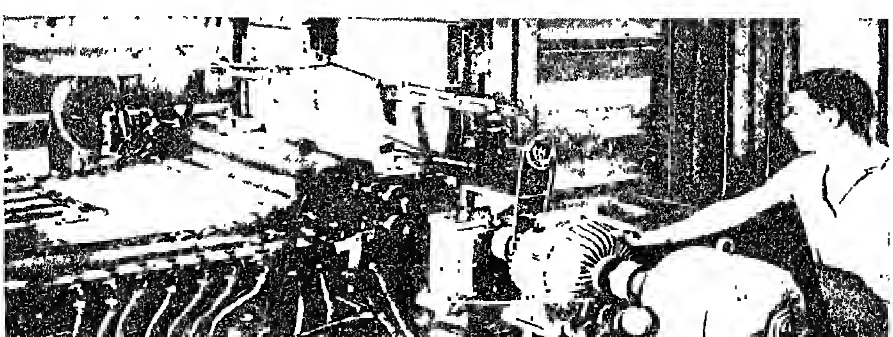


FIGURE 1.3 *Glass Making* (*Ancient*)

method is much simpler and quicker. As a result, glass articles thus produced were much less expensive and also vastly better in quality. Soon the old glass industry based on the obsolete 'core-mould process' died down and a new era in the history of glass began in the Roman Empire. Thenceforth, articles of common utility such as drinking vessels, lamps, jars and mirrors were produced in large quantities not only for the royalty but also for the people. Many of these objects were so commonplace that they replaced clay or wooden wares almost completely. It is in this respect that the invention of the blow pipe is particularly signifi-

FIGURE 1.3 *Glass Making* (*Modern*)



cant. Even today, this ancient implement has a place of pride in a glass-house, producing various types of mouth-blown glass ware.

By this time, the method of glass making had become fairly standardised. Silica sand, soda or the ashes of the marine plants and sometimes lime were used as the chief ingredients. Most of the glasses used to be coloured due to the presence of iron impurity or addition of various minerals, although in the later period (after about 100 B.C) lighter and even transparent glasses were also produced. Figure 1.3 shows the contrast between an ancient glass factory and a modern plant (Fig. 1.4). The name Rome is famous not only for the unprecedented variety of application of glass but also for the proficieny of Roman glass makers in producing glass for aesthetic satisfaction. A classical example of Roman work is the famous vase owned by the Duke of Portland (Figure 1.5). The vase is blue in colour and has an exquisite "Cameo" relief in white.

FIGURE 1.5 *Portland Vase (Roman Period)*

The Roman empire had spread from Syria in the east to Rhineland and Normandy in the west. The important glass-making centres in the Roman empire were in Alexandria, Sidon

and then in Rome itself. From these centres the industry spread to Rhineland (Germany), Gaul (France) and various other places. One of the important reasons for the development of the glass industry during this period was that the Roman rule gave people the law and security without which art, industry and trade of any kind cannot flourish. That is why, we observe time and again, the growth and decay of the glass industry is closely related to the rise and fall of the empires. This happened in Egypt and, as we shall see, it also happened in Rome and elsewhere. Around A.D. 500 Rome was conquered by the Barbarians from the north. These vigorous people did not have the sophistication and refinement of the Romans to patronize the glass industry and soon the glory of the glass industry in Rome was gone. In the 4th century A.D., the Emperor Constantine established the new capital of the Eastern Roman Empire in Byzantine. He got the Roman glass makers settled there and soon Byzantine became the centre of a thriving glass industry under the royal patronage.

GLORY OF ISLAMIC AND VENETIAN GLASS

The other important glass making centre was in Syria Damascus, the heart of Islamic culture, was also renowned for glass making. Although the Syrian glasses produced in the earlier period were semetic in character, a distinct change in the quality was observed with the rise of

FIGURE 1.6 *Enamelled and Guilded Glass Vase (Islamic Glass)*

Islam in the 6th century A D. The articles produced were typically Islamic with vivid repetitive patterns and a richly decorated surface. From Syria, the industry spread to Egypt and some of the other neighbouring places which the Arabs had conquered. The mosque lamps of Egypt, sometimes containing inscriptions from the Koran, are exquisite specimens of Islamic glass (Figure 1.6). In some of the Islamic glasswares, the Chinese influence was also noticeable indicating the cultual intercourse between these two civilizations during the Middle Ages.

FIGURE 1.7 *A Gothic Window Made of Stained and Painted Glass (14th Century AD)*

One of the important contributions that the Syrians made towards glass technology was the invention of a new method for producing flat glass which came to be known as 'crown glass'. First a red hot pasty mass of glass is gathered at the end of a blow pipe and is then blown into a large 'bubble'. A solid rod is then struck at the opposite end of the 'bubble', and it is cracked off from the blow pipe. The hot bubble of glass still fairly soft, is then spun by rapidly rotating the rod till, due to the centrifugal force, the soft bubble flares out and ultimately flattens. The flat glass made in this way came to be known as 'crown glass'. Byzantine

artisians of Constantinople (by then the city of Byzantine was renamed after its founder, Emperor Constantine) ultilised the method for producing stained glass windows which found a place in some of the great cathedrals of the Christian world (Figure 1.7).

After the middle of the 13th century A.D., Damascus was repeatedly attacked by the Turks and Mongols and finally, in the year 1402, Tamerlane, another Mongol, ransacked Damascus and took away the glass-blowers to his capital at Samarkand. That was the end of glass making in Damascusb ut the story of glass goes on.

During the middle ages, a number of trading cities sprang up in Europe, and Venice was one of them. The Venetians acquired the knowledge of glass making from the East. They took away some of the Byzantine glass-blowers from Constantinople, which they happened to occupy for some time. With the help of these artisans they developed the industry in their own land and soon Venice became the most important glass-making centre in the world. The industry in Venice flourished so much that it had to be removed to the nearby island of Murano to avoid any chance of a fire and also to ensure that the secret of glass making did not leak out to the outside world. Although some of the glass makers used to enjoy a high position in the society, any attempt to emigrate was made punishable by death, to ensure for Venice a monopoly in the glass trade. Bowls, bottles, mirrors of various styles and descriptions used to be made and exported in large quantities to different parts of Europe and the Near East.

During the 13th and 14th centuries A.D., the wave of Rennaissance was sweeping through Italy and there were outstanding developments in painting and sculpture. Struck by this spirit the Venetian glass makers developed a transparent and almost colourless

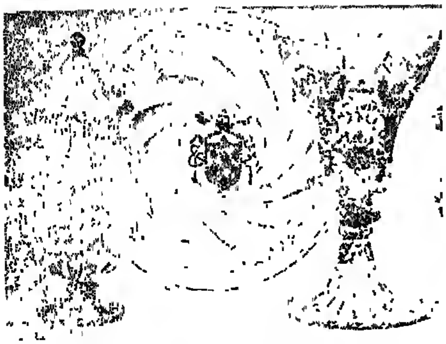


FIGURE 1.8 *Venetian Crystallo (16th Century AD)*

glass which came to be known as "crystallo". The glasses made by Egyptians, Romans and Syrians were generally opaque, translucent or coloured. The emphasis had been on imitating precious stones or on surface decoration. Now, with the colourless "crystallo", the glass makers could produce articles of such delicate beauty as belonged to glass and glass alone (Figure 1.8). It was not a false gem but true glass with its brilliance and transparent purity. Indeed, that was the time when glass came into its own. The development of "crystallo" was followed by a number of discoveries which are most significant in the history of science. The principles of the microscope and telescope were discovered by the Janson brothers in Holland around 1600 A.D. A crude version of the camera was invented in 1667 by Della Porta in Italy and the liquid in glass thermometer by the Duke of Tuscany in 1654. In all these instruments, lenses or tubes made of colourless glass were used. In fact, crystallo was the forerunner of the modern optical glass.

Venice could not hold its secret very long. By the end of the 16th century, some of the glass makers emigrated at the risk of their lives to different parts of Europe. Venice lost her monopoly in the trade but Europe gained a new art and technology.

Venice was not, however, the only place to produce glass. There was another important glass-making centre also in Italy at Altaire near Genoa. Unlike the Venetians, the glass makers of

Altaire were encouraged by their "Association" to go abroad and they even had the so-called "University for glass-making". Travelling further North, Venetians found a native tradition in glass-making in Germany and other parts of Europe dating back to the Roman period. Most of the glass makers in these countries were nomadic people of Eastern origin. They generally stayed near the forests, from where they got wood for fuel and produced a green variety of glass which was called "wald glass" (forest glass). The impact of Venetian style on the old German tradition brought a vigorous revival in glass-making in Bohemia. They developed a hard glass composition which was particularly suitable for engraving. We find that in the later part of the 17th century the technique of engraving on glass surface with an abrasive wheel or a diamond point (Figure 1.9) was so well developed that it began to rival the old art of enamelling (Fig. 1.6). The Bohemian and Dutch craftsmen were specially renowned for their excellence in engraving work.

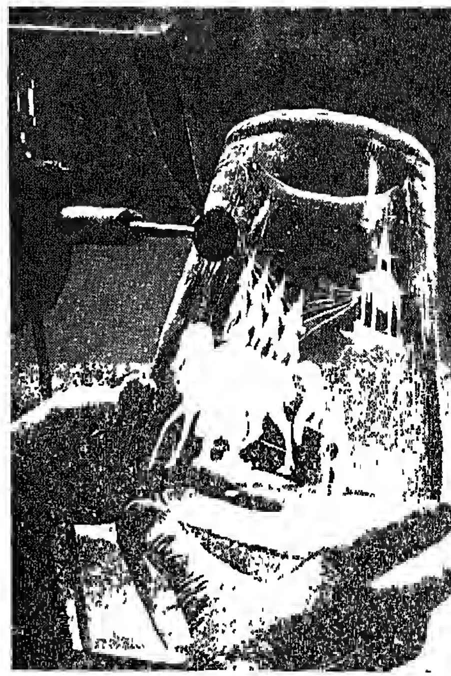


FIGURE 1.9 *Engraving on Glass in Steuben Glass Works, Corning, New York*

In 1575, a Venetian glass maker, Verzelini was granted the right to manufacture glass in England by the then ruler of

England, Queen Elizabeth I, on the condition that he would teach the craft to the English. This was virtually the beginning of the glass industry in England and a century later England not only attained self-sufficiency in the industry but was also exporting glass. An important British contribution to glass-making was the discovery of "flint glass" by an Englishman, George Ravenscroft (1675). This new variety of glass, containing substantial amounts of lead was transparent, heavy and looked more brilliant because of the high refractive index. Also, the glass was comparatively softer and could be conveniently cut into intricate shapes. (Fig. 1.10). By the beginning of the 18th century, English cut glass became renowned all over the world and with the expansion of the British Empire the glass industry had a flourishing trade overseas. Many of the important centres producing the famous English cut glass are in or around the town of Stourbridge. Besides Bohemia, Stourbridge and Belgium, some of the other famous names associated with the production of artistic glassware in the contemporary period are Orrefes and Kosta of Sweden and Steuben in Corning, New York.

FIGURE 1 10 *English Cut Glass*

SCIENCE AND GLASS

From the earliest times the processes involved in making glass were kept as closely guarded secrets, often confined to the family of the glass makers. The operations were entirely empirical and the emphasis had been more on the skill and workmanship of the craftsman than on understanding the processes involved in producing glass or the behaviour of glass as a material. Naturally, the progress was extremely slow and some of the technological breakthroughs made in the long history of glass-making were the results of some fortunate accidents and not of any rational effort. We can realise how true this was when we consider that the Egyptians were making glass by more or less the same 'core-mould process' for over a thousand years before somebody discovered the simple blow pipe.

The necessity for understanding glass as a material was felt about a century ago when the scientists started using glass as a tool for scientific research. In the year 1880 a significant development took place when Ernst Abbe, a German physicist, joined hands with a young chemist Otto Schott to make systematic studies on the effect of chemical composition on the optical properties of glass. Under the patronage of the Prussian Government, they started the first research laboratory devoted to the studies on glass science and within a few years a German firm began producing optical glass which was acknowledged to be the finest in the world, much better than that produced in France or England by the old traditional methods. In fact, both these countries became heavily dependent on the German glass for making optical instruments such as microscopes, telescopes, cameras, etc. This phenomenal success of the German enterprise was, in fact, the triumph of science over empiricism. When World War I broke out in the year 1914, the

import of German glass in Britain was stopped and this was the time when the importance of research for the development of the glass industry was keenly felt in that country. In 1915, a teaching-cum-research centre was started in Sheffield under the leadership of W.E.S. Turner, who later came to be known as the "father of the modern glass technology". In the subsequent decade several other research establishments were started in different countries and facilities were created for teaching the science and technology of glass. In most of the advanced countries of the world a large number of scientists are now working on various problems related to this versatile material, glass.

The impact of mechanisation on the glass industry was felt during the turn of the last century. The old blow pipe which had been in use since the Roman period gave way to automatic machines turning out glass articles at astonishing rates. Today, there are machines which can produce over 200 penicillin vials or several feet of flat glass per minute. This phenomenal increase in the rate of production has brought the price of glass articles within the reach of the common people. At the same time researches led to the development of a large variety of glasses having most unusual properties. There are glasses that are harder than steel and some others are softer than wool. Some can float on water while a few others are heavier than some metals. Today, glass is being produced not only to meet the daily necessities of modern man but it also plays a vital role in the development of science and industry. Glass and ceramic products are used for harnessing atomic energy, in making electronic computers and in the construction of missiles that are hurled into outer space. We shall have occassion to look into some of these later in this book. For the present, let us turn to the Indian scene.

THE INDIAN SCENE

History tells us of the great civilisations of the ancient world that were developed along the river Nile in Egypt, the Tigris and Euphretis in Mesopotamia, the Ho in China and the Indus and the Ganges in India. We have already discussed the Egyptian and Mesopotamian glasses The art of glass-making is also believed to have been known to the ancient Chinese. It would, therefore, be surprising to find that glass was not made in ancient India. Comparatively recently, some important archaeological discoveries have been made which reveal that the art of glass-making was in fact known in ancient India. Pieces of glass and clay crucibles used for glass-making have been found at a place near the town of Basti in U.P. (Figure 1.11). These are the remains of a glass factory which was probably in operation some 2,300 years ago. Several glass articles including beads, tiles and conical flasks have also been excavated from Taxila, another important seat of ancient civilisation. Chemical compositions of some of the glasses excavated from Taxila are stated to be similar to those of the Assyrian

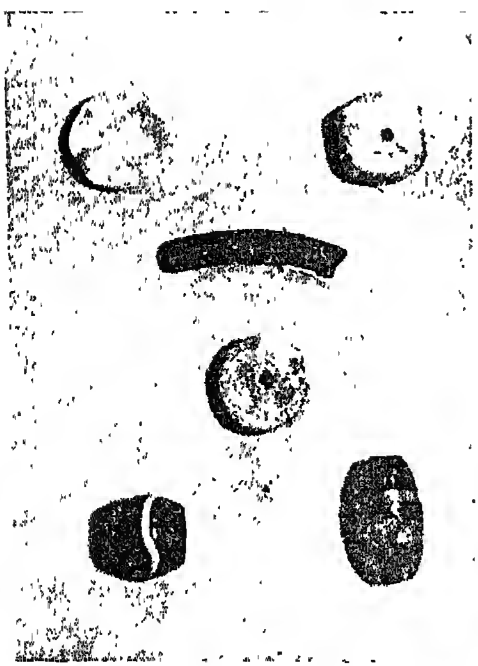


FIGURE 1.11 *Glass Beads from Basti, U.P. (about 2,500 years old)*

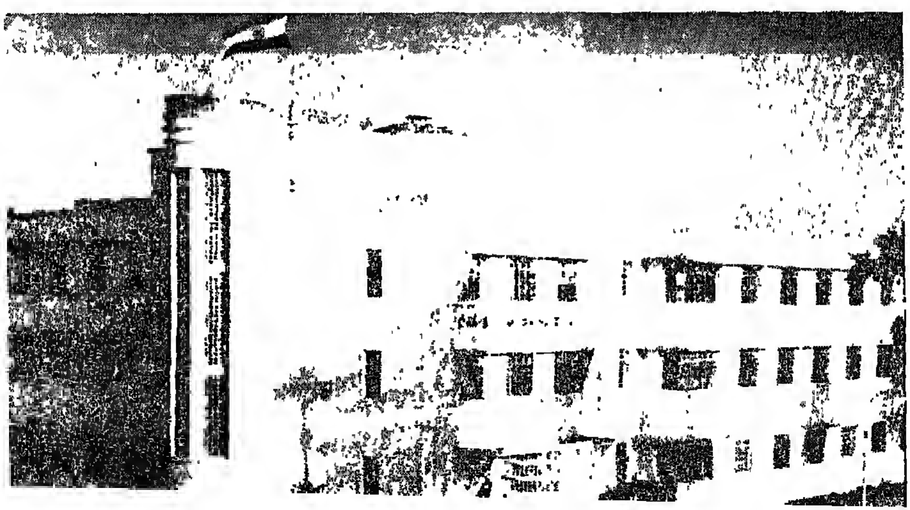
glasses of the same period. In a few specimens, the presence of lead, barium, etc. were also detected although the use of such ingredients in glass-making was generally believed to be unknown to the ancient world. During the Mughal period the art of glass-making was well known and Shishgars (glass technicians or artisans) were flourishing in the Middle Ages. The present state of our knowledge of the interesting subject of glass-making in ancient and medieval India leaves much to be desired and it is hoped that future researchers will be able to throw more light on this field.

Turning to the contemporary period we find that the first glass factory to be established in the Indian Union during British rule was the Pioneer Glass Works in Titaghar (1890). A landmark in the history of Indian glass is the Paisa Fund Glass Works established at Telegaon near Poona in 1908 with the blessings and guidance of Balgangadhar Tilak. As the name shows the funds for starting the factory were raised by public contributions of only one paisa each. Not only did the factory survive the extremely unfavourable conditions then existing in our country under foreign rule, but it also turned out a number of technologists and operators, whose services were later utilised in newer establishments. Indeed, this small unit served as the nucleus of the glass industry in our country. During these early days some of the well-known personalities who made notable contributions towards the development of the Indian glass industry were Iswar Das Varshnei (Seraikella Glass Works), Pandit Vishnu Dutt (Ganga Glass Works) and the Ogales (Ogale Glass Works). These pioneers of the industry had to struggle almost constantly against foreign imports during the period between the two World Wars.

With the outbreak of the Second World War the import of foreign glass was heavily cut and conditions became favourable for

the growth of the indigenous industry. By 1945 we notice that there were as many as 174 factories in the country turning out about 1.4 million square metres of sheet glass and over a hundred thousand tonnes of other types of glass. However, the systematic development of the industry, started only after Independence, particularly during the Five Year Plan periods, and new units are still coming up for producing varieties not made in the country before. In addition to the sheet glass and container glass, the industry is now producing plate glass, heat resistant glass, fibre glass, thermometer tubes, vacuum flasks, optical glass and many other varieties. Today hardly any glass is being imported and there is also a sizable export trade. The quality of the products has also improved very considerably during the last couple of decades and many of the articles are being produced according to the specifications laid down by the Indian Standards Institution. In spite of these impressive achievements we still have to go a long way to catch up with

FIGURE 1.12 *Central Glass and Ceramic Research Institute in Calcutta*



the other industrially developed countries of the world. For instance, the quantity of glass consumed per capita per year in U.S.A. is about 45 kg whereas the corresponding figure for India is only 0.5 kg or so.

The importance of scientific research for the industrial development of a country is being increasingly realised in recent years. After independence, it was felt that rapid industrial growth should be backed by suitable research facilities. With this end in view, the Central Glass and Ceramic Research Institute was established at Calcutta in the year 1950 by the Council of Scientific and Industrial Research. (Fig. 1.12). The main function of this Institute is to undertake researches on various subjects having a bearing on the science and technology of ceramic materials, such as refractories, enamel, pottery ware, mica and glass. The institute carries out survey, evalution and beneficiation of ceramic raw materials of the country, develops processes for producing articles not made in the country and for improving the quality of production. The crowning achievement of the Institute was the development of the process for making optical glass.

Some Landmarks in the History of Glass-Making

B.C. Around 70,000	Man shaped various primitive implements such as knives, arrowheads, etc. out of natural glass (obsidian).
Around 3,000	Discovery of glass-making by man probably somewhere in the Middle East.
Around 1,200	Egypt — an important glass-making centre. The technique of pressing in open moulds was developed.
Around 300	Glass-making near Basti, U.P., India. Discovery of blow pipe in Phoenicia.
A.D. 1	Glass-making under Roman rule. Production of glass articles of common utility. The art of making clear and colourless glass was discovered.
400-1300	Glass-making in Constantinople, Baghdad and Cairo (Islamic glass).
1200	Venice dominates the field.
1590-1910	Microscope, telescope and thermometers developed in Europe.
1674	Discovery of lead glass by Ravenscroft in England,

1790	Production of optical glass achieved by stirring.
1880	Systematic scientific researches on properties of optical glass by E. Abbe and O. Schott in Germany. German supremacy in optical glass production.
1903	Development of automatic machines for production of glass containers in United States.
1908	Establishment of Paisa Fund Glass Works in Telegaon, Maharashtra.
1910-1920	Mechanisation of glass industry and opening of important centres for scientific research and teaching. Development of heat resistant Pyrex glass and toughened glass.
1934	200″ mirror disc cart for the Telescope at Palomer Observatory in United States.
1946	Opening of the Central Glass and Ceramic Research Institute in Calcutta, India.
1951	Rapid development of the glass industry in India.
1962	Optical glass produced in India.

2

Glass-Making in Modern Times

If we heat silica sand to a temperature of about 2000°C, the mass will melt to form a thick syrupy liquid. On subsequent cooling the melt would form a rigid glassy mass. A sand grain is actually a tiny crystal of quartz, which is one of the many crystalline forms in which the material silicon dioxide (SiO_2) or silica, as it is called otherwise, can exist. The silica glass formed by melting sand has many favourable features that make it an ideal material for fabrication of common articles of glass such as, containers, window glass, laboratory glass wares, etc. It is, for instance, highly resistant to the weathering actions of wind and rain to which

our window glasses are exposed, and to the chemical attack of the various corrosive materials that may be put in a glass container. It can also stand shocks due to sudden changes in temperature during sterilisation and pasteurisation of milk, etc. to which glass containers may be exposed.

TYPES OF GLASS

In spite of all these advantages silica glass is used in only very special types of equipment and expensive laboratory apparatus, such as, ultraviolet lamps, etc. The reason is that there are practical difficulties in melting silica at such high temperatures, which cannot be easily attained in commercial furnaces. For large scale production of ordinary glasses that we see and use in our daily life, it is necessary to bring down the melting temperature by the additions of other appropriate ingredients called fluxes. Washing soda whose chemical name is sodium carbonate is generally used as the fluxing ingredient for glass making. However, from a glass made of soda and silica sand, the soda is easily extracted by acids and even by water. The chemical attack on the surface would not only make the glass weak and opaque but the contents of the bottle made of such glass would also be spoiled due to contamination. It is, therefore, necessary to prevent extraction of large amounts of alkalies from the glass by adding other suitable ingredients to the glass composition. One such stabilising ingredient commonly used is lime (calcium oxide, CaO) It is incorporated in the glass composition by adding calcium carbonate ($CaCO_3$) as one of the raw materials. During the process of melting of these raw materials to form glass, carbon dioxide gas (CO_2) goes off from sodium and calcium carbonates, leaving sodium oxide (Na_2O) and calcium oxide (CaO) in the glass composition. Sometimes, oxides of magnesium,

aluminium, etc. are also added as stabilisers to the glass. All these ingredients also lower the melting temperature of glass but the presence of too much of some of these oxides in the composition may tend to precipitate crystals during cooling of glass and render the glass opaque, weak and useless. These preliminary considerations show that the commercial glass compositions are so adjusted that the best possible compromises are made among various properties which determine the melting characteristics of glass and its useful-

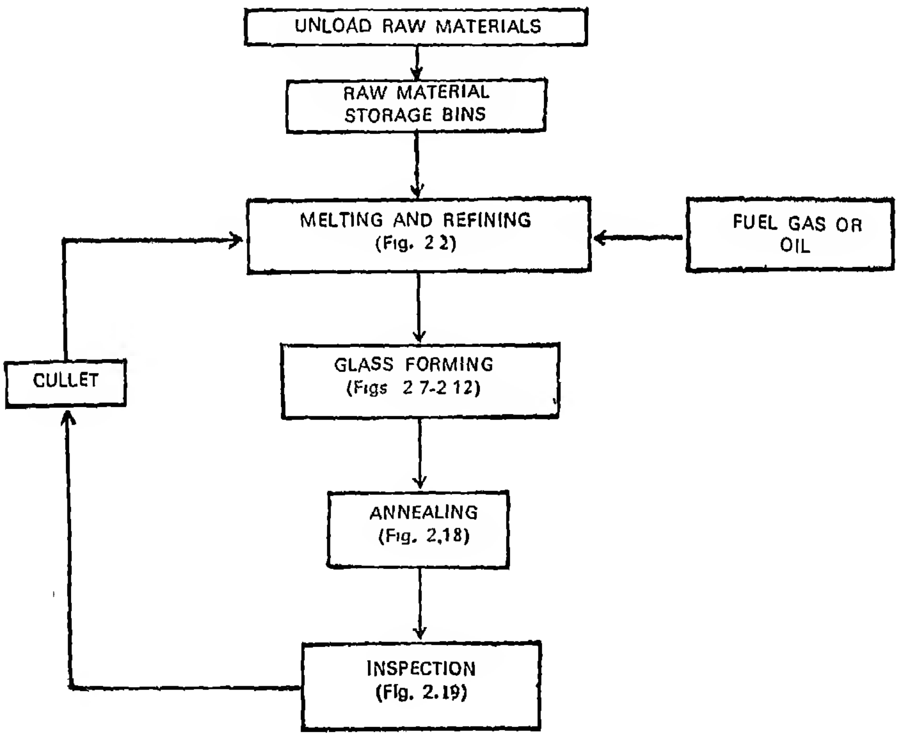


FIGURE 2.1 *Different stages of modern glass melting*

ness in actual service. By and large, the commercial glass compositions melted for the manufacture of containers, tableware, window glass, fluorescent tubes, etc., are made of mixtures of silica sand, soda and limestone. This so-called soda-lime glass constitutes the bulk of commercial glass produced. The typical compositions of various glasses used for making common glass articles are shown in Table 2.1. (See Appendix 1.)

Borosilicate glass: Boric oxide (B_2O_3) is another important glass forming ingredient which has the interesting property of lowering the melting temperature of silica glass without unduly affecting its chemical stability, thermal shock resistance and some of the other useful properties of glass. Based on these observations quite a different type of glass was developed some forty years ago largely as a result of researches carried out at the Corning Glass Works in the U.S.A. This composition, commonly known under the trade name "Pyrex", consists of a much larger proportion of silica, 82 per cent or so, and a minimum amount of alkalies (some 5 per cent), the rest being mostly boric oxide. Compared to the common soda-lime glass, this type of composition melts at comparatively higher temperature (around 1650°C) and is more expensive. But it has the useful property of high resistance to the shock due to sudden changes in temperature. This is because the thermal expansion of this glass is comparatively low. For instance, the co-efficients of thermal expansion* of vitreous silica is 5×10^{-7} and for the borosilicate glass it is nearly 32×10^{-7} whereas, for a typical soda-lime glass the value is around 80×10^{-7}.

The borosilicate glasses are highly resistant to the chemical attacks of water and acids. Beakers, flasks and various other laboratory glass apparatus that are used in laboratories for experiments involving the use of corrosive chemicals, are made of boro-

silicate glass. Also, for handling and storage of corrosive materials in the chemical industry, large containers, pumps, etc., are lined with borosilicate glass. Glass pipes, high tension electrical insulators and various other glass articles, which may be exposed to strong chemical action, high electrical voltages or to sudden changes in temperature during use, are also made of this type of glass.

Comparatively recently, a novel method has been developed for producing silica glass. Although the melting temperature of silica is very high, a mixture of silica with about 20% boric oxide and small amounts of alkalies, etc , can be easily melted at temperatures around 1450°C. However, on slow cooling this glass does not remain clear, a glass composition rich in boric oxide separates out from the silica glass, like drops of oil in an emulsion of oil and water. When this solid emulsion of two glasses is treated with an acid solution, the boric oxide rich is dissolved leaving a skeleton of porous silica glass. On reheating the silica glass to about 1400°C it softens and the pores are closed. This type of glass, initially melted at a much lower temperature has practically all the advantages of pure silica glass which were discussed earlier

Although, the bulk of commercially produced glass articles is made of soda-lime glass or borosilicate glass there are numerous other varieties of glasses that have been developed as a result of systematic scientific researches, particularly during recent years. In fact, oxides of most of the elements as also some of the sulphides, selenides, arsenides, etc. can be incorporated in special glass compositions to varying extents. Some of these special glasses having unusual physical and chemical properties are used for producing different optical instruments such as microscopes and telescopes, electrical insulation, electronic devices and various other items of

equipment. Later in this book we shall discuss more about some of these special glasses that are used in industries, laboratories, and in the modern home.

RAW MATERIALS

Major constituents: By and large, the principal glass forming raw materials used for the production of soda-lime glass are silica sand, common soda and limestone. For the manufacture of glass articles by the modern automatic processes it is essential that the materials should be of appropriate quality and uniform composition. Iron oxide is a common impurity that is almost invariably present in sand, limestone, felspar and some of the other minerals used for glass melting. This impurity produces an undesirable greenish tint and is, therefore, avoided as far as practicable. This is particularly important in the production of optical glass used for making lenses, prisms, etc. The amount of iron oxide that is generally permissible in such glasses is not more than eight parts or so per 1,00,000 parts of glass. The size of the sand grains is also important. If these are too fine, these will be blown away from the furnace whereas coarse particles of sand will not readily dissolve in glass. Sand that is suitable for glass making occurs in several places in our country. For the industry in Northern India most of the glass making sands come from Shankargarh (Naini), Burgarh and a few other places in Uttar Pradesh. There are also good deposits near Bundi, Sawai Madhopur and Thar in Rajasthan. Some of the quartz occuring in Hyderabad, Eastern Bihar and Salem in the South contain very little iron and they are used for making colourless glass wares. Many of the factories in the Southern and Western regions of the country use the mineral instead of sand, after crushing large lumps to a powder.

Good quality limestone suitable for the glass industry occurs in Satna and Katni areas of Madhya Pradesh, Jodhpur and Alwar districts of Rajasthan and near Dehra Dun in U.P. Like quartz, limestone also occurs as massive lumps which are crushed, ground and seived before use.

Sodium carbonate or soda is a chemical produced in factories in Mithapur, Porbunder and Dhrangadhra in Gujarat and Banaras in U.P, and in certain other places. The common washing soda is in a finely powdered form. This form of soda is called 'light' soda ash and is not quite suitable for use in glass melting because some of it will be easily blown away from the furnace during melting. The material preferably used by the glass industry is "heavy" soda ash, a coarsely crystalline form obtained by recrystallising the light soda ash. There are also natural deposits of soda in various parts of the world, such as those in Magadhi in East Africa. Although not quite as pure as the synthetic soda ash, they are coarse grained and contain small amounts of fluorides which favour melting of the raw materials. Another important raw material used as a major constituent in borosilicate glasses is borax and boric oxide which used to be mostly imported but are now being processed in our country from imported crude borax.

Minor ingredients : So far, we have considered only the major ingredients which constitute the bulk of the glass composition. In addition to these there are a number of other ingredients which are added in small amounts. These minor ingredients play important roles in melting of glass and, therefore, merit separate consideration. Some of the important minor ingredients are magnesium oxide (MgO), aluminium oxide or alumina (Al_2O_3), arsenous oxide, fluorides, nitrates, sulphates, etc. Magnesium oxide is incorporated in the glass composition by adding magnesium carbonate or

dolomite, a mineral containing both magnesium and calcium carbonate. Alumina generally comes from the mineral felspar which is an alkali aluminium silicate ($Na_2O.Al_2O_3.6\ SiO_2$). Fluorides make the molten glass more fluid and thus facilitate melting. Certain minor batch ingredients such as arsenous oxide, potassium nitrate, sodium sulphate, barium sulphate, etc. decompose under the influence of heat during the process of melting and as a result, large quantities of gases are generated in the melt in the form of bubbles. During escape of these gases through the molten mass of glass, smaller bubbles of air entrapped in the melt and other gases are also removed. In this way they facilitate refining of glass and are therefore known as the refining agents.

Most of these refining ingredients also help in removing the undesirable greenish tint due to the iron impurity that finds its way into glass from sand, limestone, etc. As we have learnt in chemistry, in compounds of iron, the element can be present in two states of oxidation, namely the ferrous and ferric state. In glasses also these two forms have been found to exist. In the ferrous state iron produces a bluish green colour while the ferric form is almost colourless The refining agents also act as 'oxidising' agents and convert most of the coloured ferrous iron to the colourless ferric state. Although the colour due to iron becomes very much lighter as a result of partial "oxidation" of the ferrous to the ferric form, a light green colour is still perceptible. To mask this residual colour, another colour producing agent such as selenium is added in very small amounts (about 1 part per 10,000 parts of batch) to produce a faint reddish tint. The two colours, red and green are made to balance each other (complimentary colours) so that they may combine to produce a grey shade which is not easily perceptible. To obtain a more perfect balance of colour, traces of cobalt

oxide are also added. By this process, the glass is made to appear colourless although there is actually a natural grey shade which is not easily perceptible.

Coloured glasses of various shades are produced by adding different ingredients. As we know copper sulphate crystals dissolve in water to produce a solution of bluish green colour. Similarly, oxides of copper and certain other elements are soluble in molten glass and the "glass solution" so obtained becomes coloured due to the presence of these elements. Oxides of copper and chromium produce bluish green and green colour respectively. Titanium and manganese oxides impart violet tints while cobalt oxide gives deep blue and nick purple. This type of colour is known as the solution colour. In addition to these colouring oxides there is another group of colouring ingredients which does not remain dissolved in the glass but stays dispersed in the form of very fine particles. The earliest known colouring material of this type is gold. Chemical salts of gold such as gold chloride is added to the glass batch in very small amounts to obtain a fine dispersion of gold particles which produce a pleasant purple tint in glasses. A bright ruby red colour is obtained by precipitation of crystals containing sulphides and selenides of zinc and cadmium. Similarly, cuprous oxide produces a ruby colour and cadmium sulphide yellow.

MELTING OF GLASS

Tank furnace: The raw materials for glass-making are first mixed in requisite proportions and then the mixture called 'batch' is fed into the melting furnace. In modern glass practice the melting operation is generally carried out in a 'tank furnace'. Figure 2.2 gives a diagrammatic view of a typical tank furnace. As the name indicates, it consists of a rectangular tank into which batches

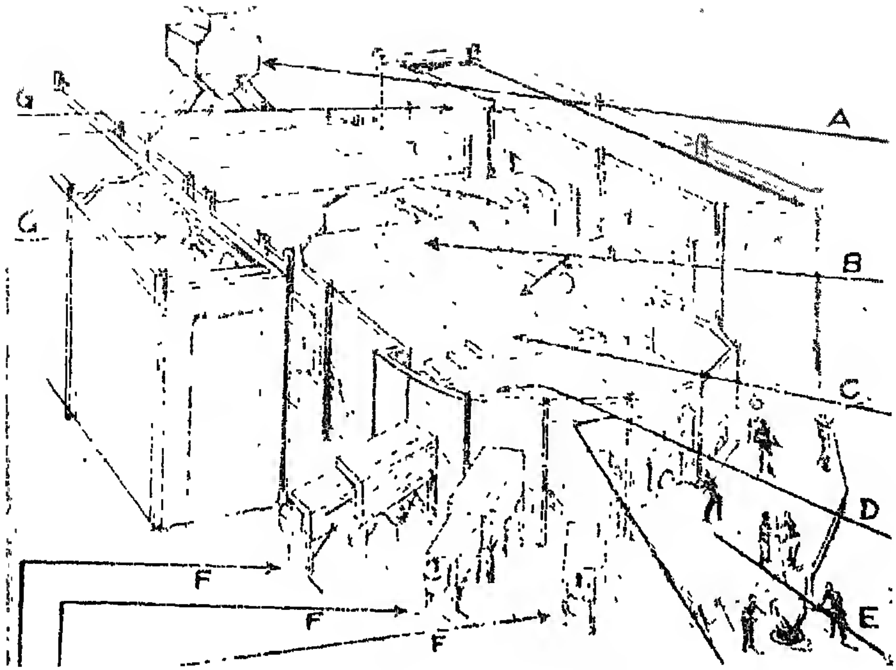


FIGURE 2.2 *Glass melting Tank Furnace (A) storage bin containing raw glass forming mixture, (B) flames sweeping over molten glass in the "tank, (C) bridge wall separating the melting end from the working end (D) working end, (E) hand working of glass, (F) forehearth and (G) regenerator*

of mixed raw materials are continuously fed from one end and from the other end comes out a stream of clear molten glass ready to be put into forming machines. In many respects the design and construction of the furnace is similar to an "open hearth" furnace used for melting steel. All around the melting tank there are "side walls" covered at the top by an arch, which is also known as the "crown". Through the side walls there are openings which are called "Ports". As shown in Figure 2.3, from the mouth of the ports on one side of the furnace a mixture of fuel and air starts burning and

the flame sweeps across the tank containing a molten bath of glass. The burnt gases, still very hot, escape through the ports on the opposite side of the furnace wall. The ports at both sides of the furnace are connected to box like structures loosely packed with stacks of bricks. These structures are called "Regenerators". The hot waste gases coming out of the furnace through the exit ports are allowed to pass through the brick stacks and transfer a portion of their heat to the bricks. Finally the gases escape through an underground passage to the chimney. After periods of half an hour or so, the direction of flow is reversed. That is, the regenerator, through which the waste gases were passing is now connected by a reversal valve to the passage through which the air required for burning the fuel comes in. As the air passes through the red hot brick stacks of the regenerator it picks up the heat left earlier by the hot waste gases to these bricks. By the time the air arrives at the ports (which were serving earlier as the exit ports) it is already quite hot. The air then mixes with the fuel and the mixture starts burning at the mouth of the port. The waste gases now pass through the opposite ports to the other regenerator and thus the process of firing goes on. The function of the regenerators is therefore to recover a portion of the heat from the waste gases and then transfer it to the incoming cold air. With this arrangement the high temperatures required to melt glass are attained by spending smaller amounts of fuel. In spite of this and many other devices to improve the fuel efficiency of the furnace, hardly 20 per cent of the heat energy produced by burning the fuel is actually used for melting glass. The rest 80 per cent or so goes out mostly as radiation through the furnace walls and with the waste gases.

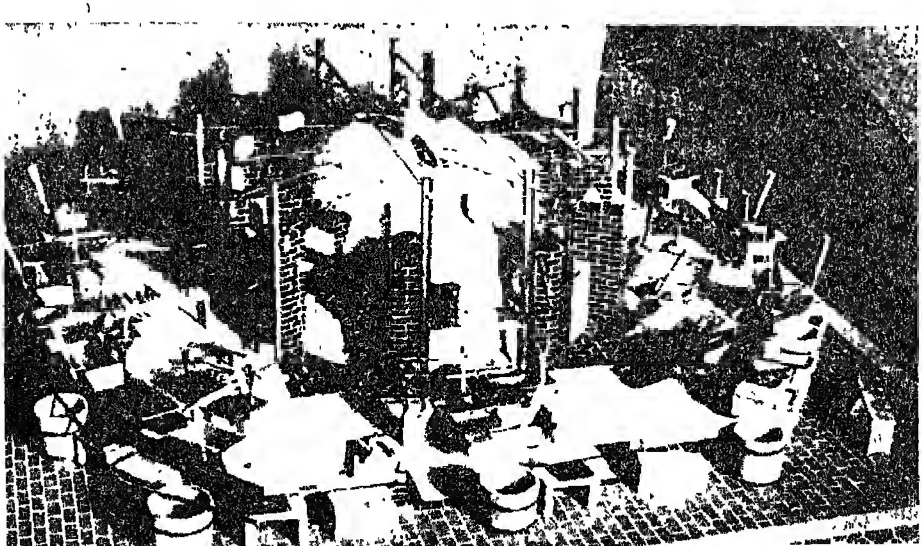
The furnace described here is a "cross fired regenerative tank furnace", which is commonly used in modern glass practice. This

however is by no means the only type of furnace used for glass melting Various other designs of widely varying sizes are also employed for the purpose. There are furnaces which are so small that hardly a few hundred kilograms of glass can be produced in a day, while some of the very large furnaces, so far constructed hold over 1,000 tons of glass.

The pot furnace, similar to the ones used in olden days (Figs. 1.3 and 2.3), is also used even now, although it is limited to melting of special types of glasses, such as coloured glass, optical glass, etc.

Fuels: The fuels generally used in the modern glass practice to heat the furnace are oil or producer gas. Producer gas is formed by passing controlled amounts of steam and air through a red hot bed of coal kept in a huge cylindrical container. Oxygen of the water molecule (H_2O) reacts with the carbon in coal to form the gaseous compound carbon monoxide (CO) and hydrogen (H_2).

FIGURE 2.3 *Model of typical pot furnace*



Free oxygen from the air also reacts with carbon to form carbon monoxide. The producer gas is therefore a mixture of varying proportions of carbon monoxide (24-28%), hydrogen (12-15%), nitrogen from air (50-55%) and some amounts of hydrocarbons, carbon dioxide, etc.

In some parts of our country natural gas is now available for glass melting. The natural gas as well as the fuel oils are primarily mixtures of various compounds of carbon and hydrogen. When they burn in air, oxygen combines with the carbon and hydrogen forming carbon dioxide (CO_2) and steam (H_2O) During these chemical reactions leading to the formation of carbon dioxide and steam, heat is produced and such heat producing reactions are known as the "exothermic" reactions. During burning of producer gas similar reactions also take place between oxygen and hydrogen or carbon monoxide, present in the fuel gas.

The use of electricity for glass melting is getting more popular in recent years, particularly in countries where cheap power is available. In India, a plant in Bangalore is melting glass with electricity, while several other units are using electricity as an auxiliary source of energy to speed up the melting rate so that glass can be drawn more rapidly from the furnace. The auxiliary electric heating device used for this purpose is known as the "boosters".

Refractories: As mentioned earlier, the temperatures at which commercial soda-lime glass is melted are generally above 1400°C, sometimes even above 1550°C. To maintain such high temperatures of the molten glass, the fuels are burnt at such high rates that the different ports of the furnace, the side wall, crown and particularly the port openings through which the flames pass become almost white hot. At such high temperatures large volumes of gases sweep across the furnace at speeds of several feet per

second. In a medium-sized furnace producing about 20 tonnes of glass per day as much as 7 cubic metres of burnt gas pass through the exit port every second.

It is, therefore, not difficult to visualise that the materials with which such furnaces are built must be of very special types. They should not only stand the very high temperature at which the furnaces are operated but should also be able to bear the load of the upper structure and resist the corroding and the eroding action of the waste gases, dust and molten glass.

The materials which possess such exceptional qualities are known as the "refractories". Various types of refractories are used for the construction of the different parts of the furnace. For instance, the tank itself holding molten glass is made of comparatively large and thick blocks which are highly resistant to the corrosive action of glass. The mineral that is extensively used for making tank blocks is "sillimanite" or its twin brother "kyanite". Some of the best varieties of this type of mineral can be found only in our country, mostly in Madhya Pradesh and Assam. Another type of material which is finding increasing use in the construction of tank, side walls and ports is the "electro-cast" refractories These are produced by melting oxides of zirconium, aluminium, etc., under intense heat in an electric arc furnace and pouring them into sand moulds of the desired shapes (Fig. 2.4). These materials are far more resistant to heat, corrosion and erosion than many of the conventional types of refractories. For construction of the furnace crown silica bricks are generally used because they have the interesting quality of bearing comparatively high load even at 1700°C at which the usual fire bricks and many other refractory materials would collapse. The bricks stacked inside the regenerator are generally firebricks or "basic" magnesite bricks.

FIGURE 2.4 *This is how an electro-cast alumina refractory looks under a microscope Large well developed crystals of mullite ($Al_2O_3.SiO_2$) are highly resistant to attack of molten glass*

Melting· When the mixed raw materials are fed into the furnace, the carbonates of sodium and calcium start reacting with silicon dioxide (silica) under the influence of heat and a series of compounds known as the silicates of sodium and calcium are formed first. Soon the mixture gets further heated when some of these silicates start melting and finally the remaining free silica in the batch is slowly dissolved in the melt to form glass.

The glass thus formed contains large volumes of entrapped air and gases. Slowly, the gases move up to the surface leaving the glass clear. This process is known as the "refining" of glass. Figure 2.3 shows that the tank is partitioned into two chambers. In one of these the batch is melted as it moves along the chamber. If there are unmelted particles of sand or entrapped gas bubbles they will be mostly on the top. The clear glass at the bottom flows through a hole into the second chamber where the glass gets cooled to a thick syrupy consistency.

Measurement of temperature: For successful operation of the tank furnace and the automatic forming machines, it is absolutely essential that the temperatures in the melting chamber, working chamber and the forehearths are accurately controlled. How are such high temperatures measured in a glass melting furnace, or

for that matter in any furnace? There are several special devices used for the purpose and one such device commonly used is the 'thermocouple pyrometer' which essentially consists of two dissimilar metals connected at one end (Fig. 2 5). The metal couple commonly used for measurement of high temperatures consists of (1) platinum and (2) an alloy of platinum with 10 or 13 per cent Rhodium.

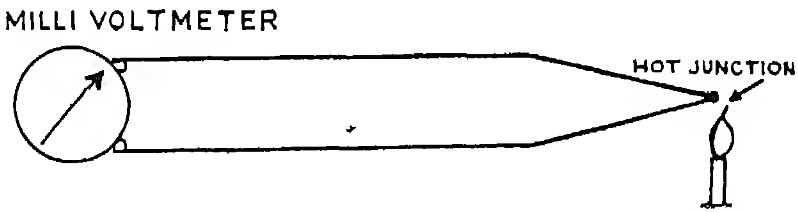


FIGURE 2.5 *Working principle of a thermocouple pyrometer for measurement of high temperature*

Wires of these two metals are welded at one of the two ends and the other ends are connected to a millivoltmeter. On heating the welded junction of the two wires a voltage is developed which is proportional to the temperature at the junction. For example, if the temperature at the junction of Platinum and a Platinum 10% Rhodium wire is 1400°C, then the voltage developed aross the wires is about 14.3 millivolts. This voltage can be measured with a millivoltmeter or more accurately, with the help of a potentiometer. Although the actual arrangement used is slightly more complex, the basic principle is more or less the same. Temperatures upto 1500°C or so can be conveniently measured by using different metal pairs. Sometimes, the thermocouple is hooked up with an electronic device that would "sense" any change in temperature and control the flow of fuel and air accordingly to maintain the temperature at any desired level. Such automatic temperature control-

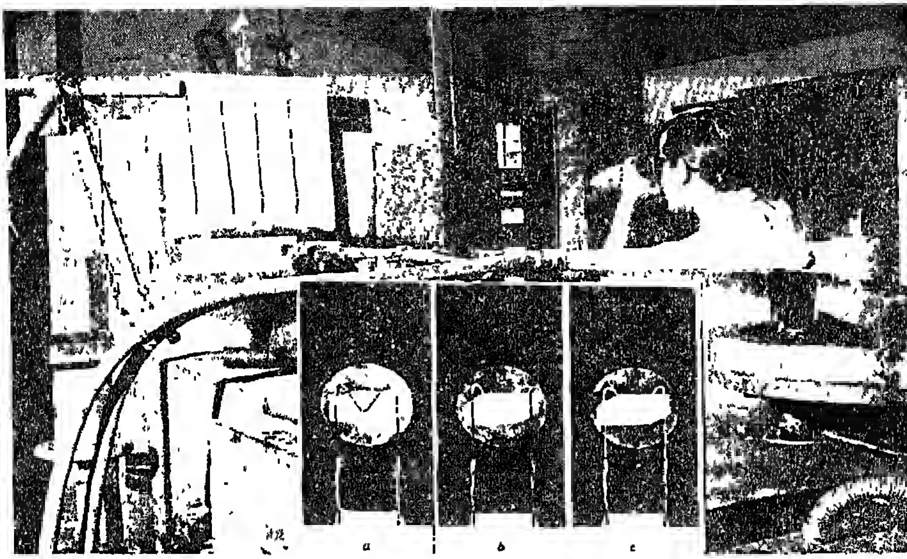


FIGURE 2.6 *Measuring the furnace temperature with an optical pyrometer. Inset shows matching of the glow of pyrometer wire with that of the furnace.*

lers are often used for efficient performance of the furnace. For measuring temperatures above 1400°C or so another device called "optical pyrometer" is also commonly used (Fig. 2.6). In this instrument current is allowed to flow through a wire and it starts glowing. The brightness of the glowing wire is slowly increased by passing increasing amounts of current through it, still the glow of the wire exactly matches with that of the furnace glow as seen through a small hole. The inset in Figure 2.6 shows matching of the glow of wire with that of the furnace. Knowing the amount of current required to match the glow of the furnace, the temperature inside the furnace can be found out.

GLASS SHAPES

Container glass: Over 70% of the glass melted goes towards making of glass containers of various sizes and shapes such as bottles, jars and other domestic glasswares. First the refined glass

from the furnace is gathered or fed into the forming machines by appropriate feeding devices The old practice was to put an iron rod into the molten glass and roll round layers of glass on the tip by rapidly rotating the rod. The rod is taken out quickly and the gathered glass is placed over a forming mould. As the soft mass of glass falls down from the rod, the right amount of glass is cut off with a pair of scissors and allowed to drop onto the mould. Although slow and old fashioned, this process of "hand gathering" is still used for feeding hand operated forming machines. The method is particularly suitable for making special types of containers produced in comparatively smaller numbers.

For continuous and automatic feeding of glass into high speed forming machines, it is allowed to flow from the melting tank into specially constructed channels (Fig. 2.2D). Here, the consistency of glass is kept at the desired level by accurate control of temperature. At the end of the channel, shaped like a boot, there is a circular orifice at the bottom and a refractory rod on top of it acts as a plunger. With every downward stroke of the plunger the desired amount of glass comes out through the orifice and is automatically cut off with a pair of scissors. Then the plunger moves up and the process is repeated. Time after time exactly the same amount of glass drops down in the form of gobs like drops of water from a dripping tap. In some of the forming machines the glass is not fed; instead, the mould of the mouth is allowed to come in contact with the molten bath of glass and it sucks in the required amount of glass. The method is not, however, quite as common as the feeding process.

The basic processes involved in shaping glass containers are two, namely, pressing and blowing (Fig. 2.7). In the pressing process the required amount of hot glass is allowed to drop into the

forming mould usually made of cast iron and then a plunger, also made of the same material, is pressed down when soft glass takes the desired shape. Tumblers, plates, bowls, glass bricks, etc. are made by this straight pressing process. The process of gathering

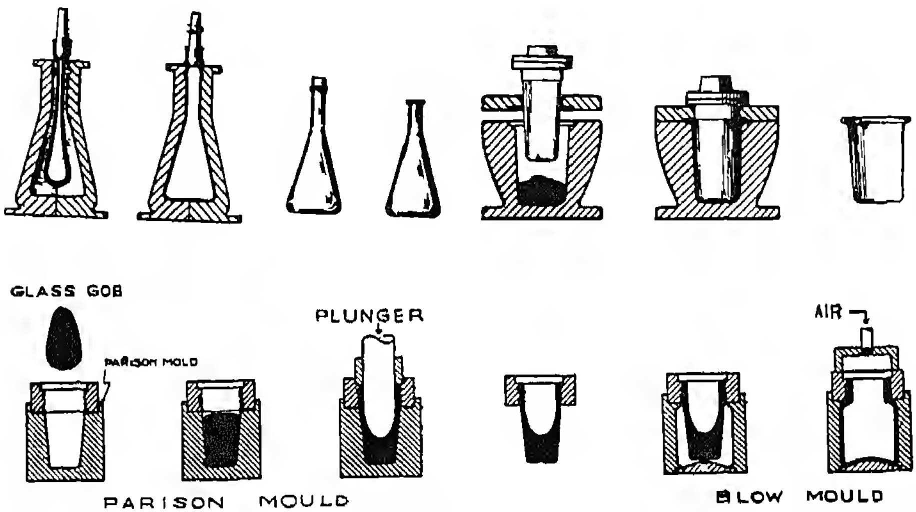


FIGURE 2.7 *Shaping glass containers by blowing, pressing and a combination of the two processes*

molten glass at the end of a blow pipe and subsequently blowing it to different forms is being practised ever since the "blow pipe" was discovered during the Roman period (Chapter I). This primitive method is, however, extremely slow and is generally used only for making special shapes, artistic glasswares, etc. In glass forming machines the articles are generally shaped in two stages (Fig. 2.8). First the glass is fed into a 'Parison mould' in which it takes the embryonic form either by pressing or by blowing with

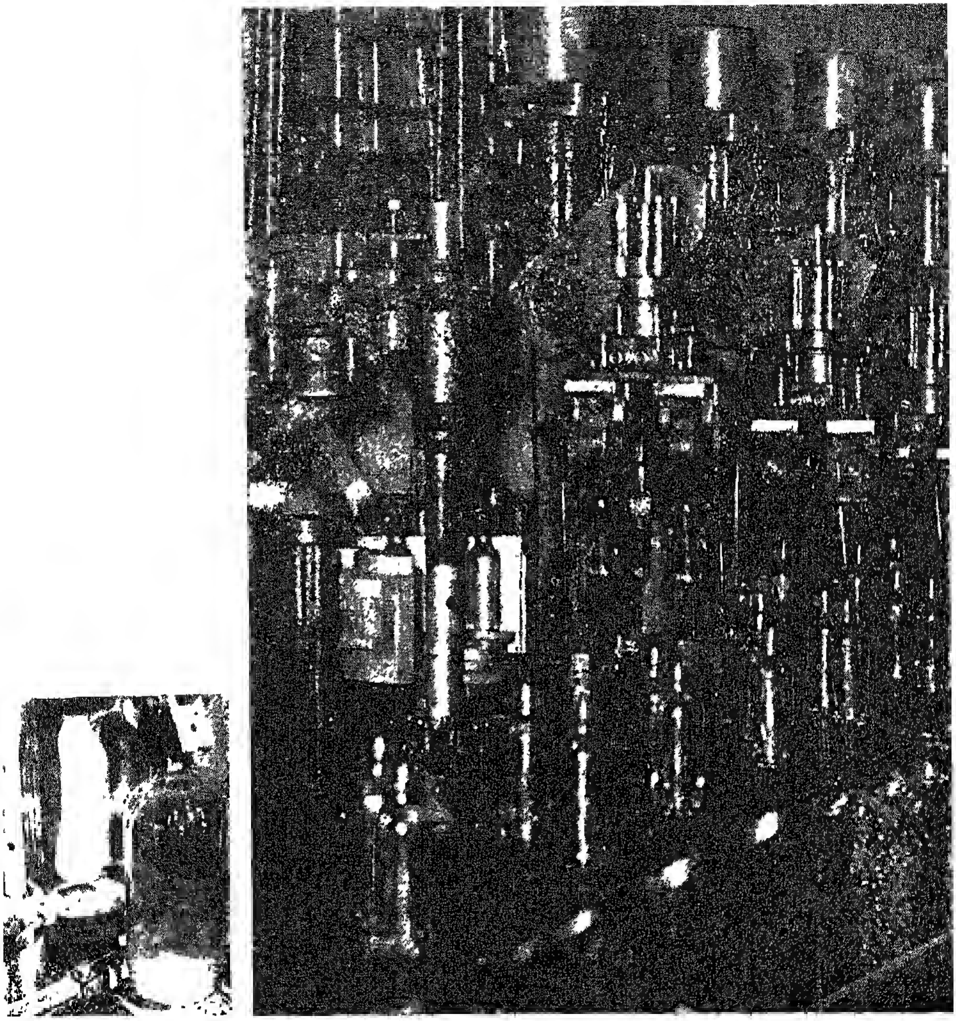


FIGURE 2.8 *Forming glass containers in automatic machines. The inset shows a finished bottle coming out of the blow mould as the next parison is fed in*

compressed air. Then it is transferred into the "Blow mould" in which it is blown to the final shape.

The blowing method is also used to produce glass shells for incandescent lamps and different types of machines are employed for the purpose, the fastest of these being the 'Ribbon machine', which can blow out as many as several hundred bulbs per minute.

With the introduction of automatic machines for manufacture of containers, the production of Indian container glass industry recorded a sharp increase from 50,000 tons in 1950 to 1,75,000 tons in 1969 and by 1974 the installed capacity is to rise to 4,00,000 tons. At the same time the quality of production improved very considerably in all respects. Technology of container manufacture is also being constantly improved upon to produce lighter and stronger bottles at even higher speeds and a major break through is expected to come shortly with the introduction of ribbon machines to produce containers at the rate of 600-800 containers per minute. To cope with the phenomenal increase in production, newer machines are also being developed for printing and filling of the bottles. There is no doubt these developments will lead to more extensive use of containers in our daily life.

Flat glass: Besides blowing and pressing, the other important processes for fabrication of glass articles involve drawing of glass while it is still soft. If the blade of a knife is put in a very thick syrup and is slowly moved upwards, it will tend to draw the thick liquid in the form of a sheet. More or less the same principle is involved in making glass sheets that are used for glazing windows. Generally, they are formed by one of the three drawing processes namely, the Fourcoult, Colburn and Pittsburg process. In the Fourcoult process (Fig. 2.9) glass is drawn vertically through the slot of a refractory boat floating on molten glass in the furnace. The glass is drawn continuously by a series of rollers. It is to be noted in the figure that

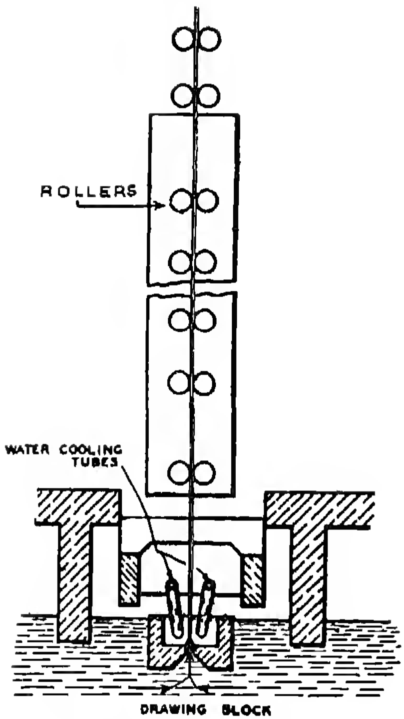


FIGURE 2.9 *Fourcoult process for drawing continuous sheets from molten glass in a tank furnace*

the rollers are so placed that they touch only the two ends of the sheet and the central portion of clean and bright sheet formed out of the molten glass remains untouched till it becomes rigid. The two sides of the sheet which are roughened in contact with the rollers are cut off from the clear central portion of the sheet. The Pittsburg process also works on more or less the same principle. The essential difference is that the molten glass does not flow through the slot of a partially immersed refractory block; instead, it flows over a completely submerged block. In the Colburn process the glass is also drawn up vertically but only for a few feet and then it is bent at right angle and moves horizontally.

Recently, quite a different process was developed by the Pilkington Brothers of England for making clear and transparent flat glass of much better quality. In all the methods described above the sheet of glass remains clear and polished because the glass does not come in contact with anything before it becomes rigid. In the Pilkington process a stream of glass flows over the surface of a molten metal. The melting temperature of the metal

is so low that as the glass flows over the liquid, it is cooled to a rigid state (Fig. 2.10). Since the glass surface does not come in contact with anything hard it remains smooth and clear.

Flat glass can also be produced by the rolling process. A continuous stream of molten glass is poured between two water

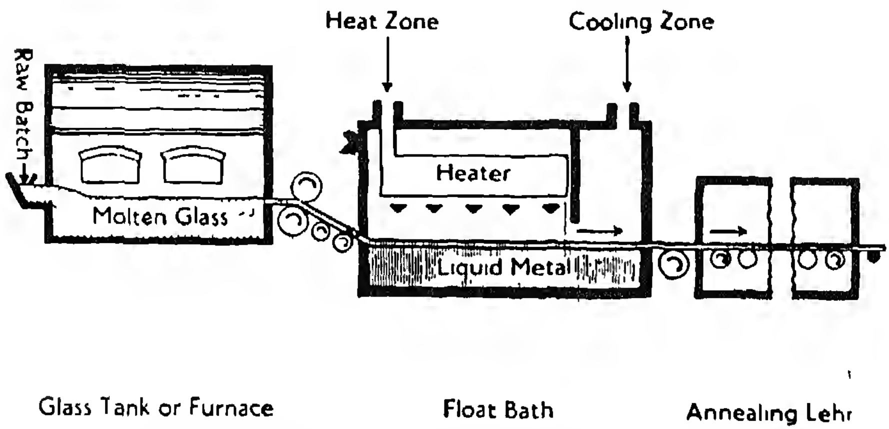


FIGURE 2.10 *Pilkington Float Process for making flat glass*

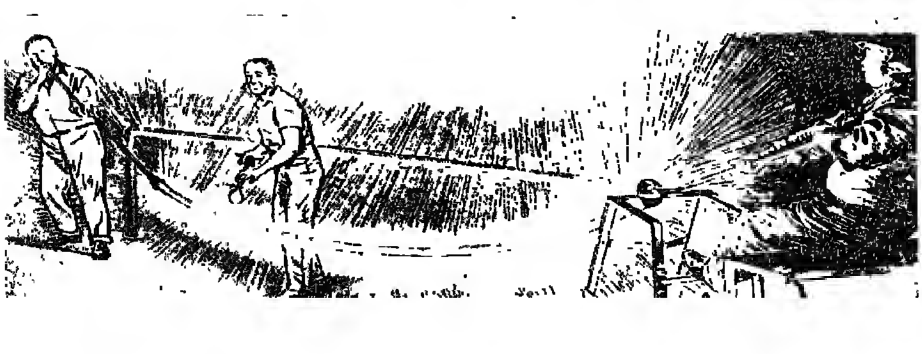
cooled iron rollers which roll the soft glass in the form of a flat, continuous plate. Sometimes various patterns are engraved on the rollers and these impressions are transferred on the surface of the glass. Such glasses containing various decorative patterns are called 'figure rolled plate glass'. When molten glass passes through the rollers sometimes a wire net is sandwiched in the glass. Use of this 'wired glass' has the advantage that if it breaks the pieces do not fly off; instead, they stick on the wire.

The surface of rolled plate glass contains the impressions of the rollers and unlike sheet glass it does not look clear. Some-

times, this translucent glass is used as such for glazing factory windows, sky lights, etc. To make the surface bright and clear it is first ground with sand, water and certain other minor ingredients. The flat and finely ground surface of glass is then polished with rouge or cerium oxide and water under a felt or cork-lined rotating disc. Polished plate glass has a much more uniform thickness than a sheet glass and it can also be made much thicker than the sheet glass. One of the important uses of polished flat glass is in the making of mirrors. Large quantities of plate glass are also consumed in the manufacture of wind shields of automobiles, aircrafts and other vehicles. There are over half a dozen factories in different parts of our country producing sheet glass and rolled plate glass.

Tubes: Glass tubes used in making fluorescent lamps, laboratory apparatus, thermometers, ampoules, phials, etc. are also made by the drawing process. A large blob of glass is first gathered on a blow pipe and then manipulated by blowing and rolling to the form of a thick-walled hollow sphere. Another rod with a flat glass disc on its tip is stuck on the red hot globe of glass and is drawn out in the form of a tube. Figure 2.11a shows how the glass is drawn out slowly by the blower by measured backward steps. The air pressure in the hollow globe of glass determines the wall thickness and diameter of the tube and is controlled by mouth. Continuous drawing of tubes is accomplished by employ-

FIGURE 2 11(a) *Drawing glass tube by hand*



ing various mechanical devices. Figure 2.11b shows a diagrammatic sketch of the 'Danner Process' commonly used for drawing tubes. The glass is fed continuously to an inclined refractory cylinder called the 'mandrel'. The cylinder rotates at a controlled speed rolling round it a layer of soft glass which is drawn towards

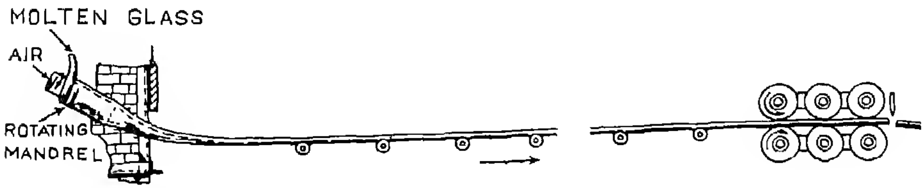


FIGURE 2.11(b) *Drawing glass tube by Danner Process*

the lower end of the cylinder. Here it meets a jet of air flowing through the centre of the mandrel and a continuous tube of glass comes out of the mandrel. Figure 2.12 shows a continuous tube of borosilicate laboratory glass formed by the 'Vello Process' in a

FIGURE 2.12 *Drawing borosilicate glass tube in a factory in Bombay by 'Vello Process'*

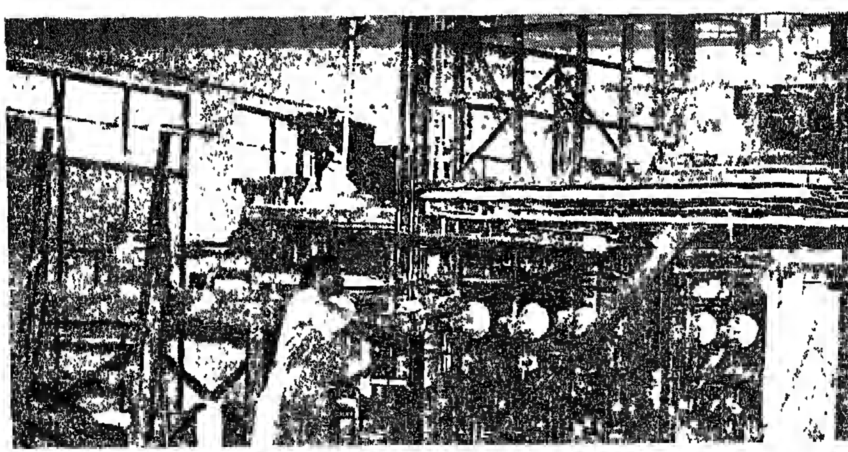


FIGURE 2.13 *Laboratory glass apparatus being fabricated from tubes by 'Table Blowing'*

factory near Bombay. In this process the molten glass flows vertically down through the annular space between two concentric refractory cylinders. Air flows through the inner cylinder at a controlled pressure, just sufficient to blow out a continuous tube of the desired wall thickness.

The glass tubes can be subsequently worked to various shapes by 'table blowing', or lamp blowing as it is called other-

wise. Figure 2.13 shows how in the flame of a burner glass tubes are softened and worked to complicated shapes. Various laboratory apparatus can be fabricated from glass tubes and rods using only a few simple implements.

Glass rods are also made by drawing glass while it is still soft. Figure 3.10 shows how a spiral rod is made by rapidly drawing a soft mass of glass round a rotating shaft of iron. The spirals are subsequently cut along its length and the individual split rings are then fused in a flame and joined to form a complete ring. Glass bangles are produced by this process and are subsequently decorated by employing various methods.

Fibre glass: Commercial production of fine fibres of glass, having a diameter around a few hundredth of an inch is a comparatively recent development. This fascinating material is generally produced in two forms, namely the staple fibres which are only a few inches long and the continuous filaments of glass. The first variety is a soft light weight material, sometimes called glass wool.

Glass wool is commonly made of soda-glass although special types of glasses such as the alumino-silicate glasses containing very little alkalies are also being used to produce fibres of special qualities. To produce glass in this form thin streams of the molten material are allowed to fall through several orifices at the bottom of the forehearth. As they come out of the orifices the streams meet jets of air and/or steam, and are broken into innumerable very fine fibres which cool almost instantaneously (Fig. 2.14a). Like flakes of snow they settle down in heaps and the loosely stacked fibres are then compressed in the form of 'bats'. Glass wool is used in this form for insulation and filtration. To produce textile materials the fibres are collected in the form

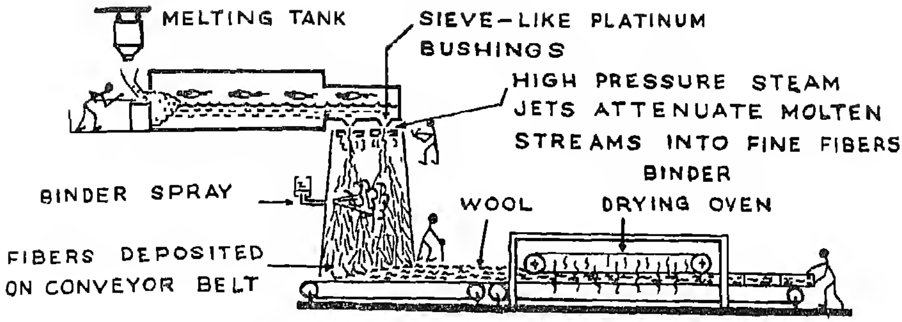
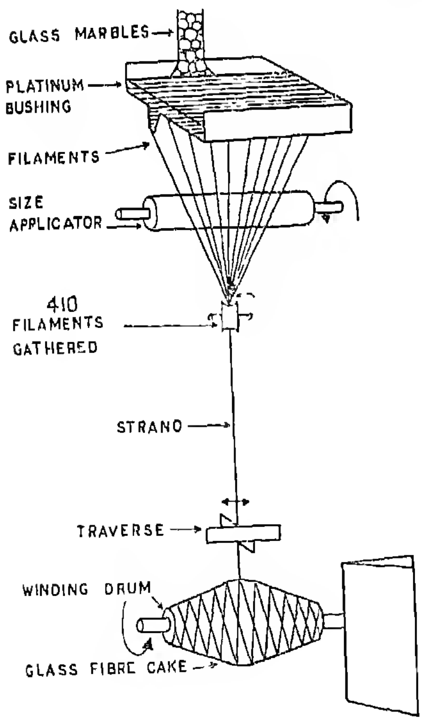


FIGURE 2.14(a) *Formation of fibre glass*



of slivers and then are spun and woven in the usual textile machines.

To make continuous filaments the glass is first rolled in the form of marbles which are then remelted in a small electric furnace. Thin streams of molten glass coming out through a large number of tiny holes are drawn and wound round spindles rotaing at high speeds (Fig. 2.14b). The drawing rate is so fast that a few kilometres of a thin glass

FIGURE 2.14(b) *Process for production of continuous glass fibres*

FIGURE 2.15 *Fibre glass products thread and cloth*

filament are drawn per minute These filaments are spun and then woven by the usual processes to form glass cloth (Fig. 2.15a). The cloth may be subsequently coloured and decorated.

Glass cloths are, naturally, fire proof and much more resistant to chemical attack than the other varieties of textile materials. They also do not crease and can be easily cleaned. Glass cloth is used for curtains, drapery, bedspreads, etc. Glass wool is also extensively used for insulation against heat, noise and electricity and also for filtration of air, chemical solutions, etc.

Bonded with plastics, the fibres form strong light weight materials which are finding numerous uses in architecture as also for making various articles of utility ranging from suitcases and fishing rods to sailing boats and automobiles This group of materials has already replaced metals in many places and newer uses are still being found. Fibre glass products are used for construction of air ducts, chemical tanks, conveyor belts, insulation tapes, etc. The production of fibre glass products in the United States during the year 1965 was over 100 million kg which shows how rapidly the use of this fascinating and versatile material is increasing in modern life. There are factories in our country

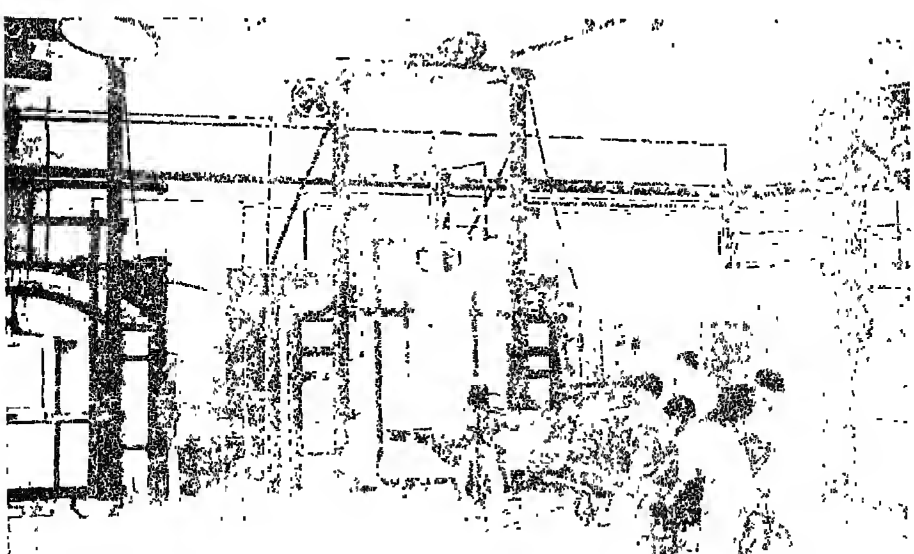
producing glass wool, slag wool and various fibre glass products. It is hoped that their use will increase substantially with further economic development of our country in the years to come.

Optical glass: In optical instruments and equipment such as microscopes, telescopes, cameras, spectrographs, etc. the vitally important components are the lenses and prisms made out of glass. The glasses used in such devices are of very special types and, therefore, they merit separate consideration. One of the important prerequisites to be satisfied is that the optical properties of the glasses should not vary beyond an extremely narrow range. When a light beam passes from one medium to another it changes direction and the phenomenon is called refraction. Refractive index gives a measure of the extent of bending of light rays. For optical glass of a particular quality, the refractive index should not vary by more than ± 0.001. Also, the glass should be free from any colouring impurity, bubbles, or any other imperfection that would distort the light rays. To meet these exacting demands, the purity of the raw materials and the manufacturing processes have to be controlled with the utmost care and precision. These technological difficulties in producing this 'eye of science' makes it one of the prized varieties of glass. Attached to the Central Glass and Ceramic Research Institute, Calcutta, there is a plant producing optical glass to meet the demands of the country. Most of the production goes for the manufacture of equipment required for the defence of our country.

To produce optical glass, raw materials of appropriate quality are mixed and fed into a white hot refractory pot kept inside a furnace. When the ingredient melts to a clear glass it is stirred with a refractory rod for hours to ensure that the liquid is thoroughly mixed. The glowing red-hot pot is then taken out of

the furnace and allowed to cool slowly to room temperature (Fig. 2.16). The pot is broken and chunks of glass are taken out and sorted. The good pieces are reheated in another furnace till they become just sufficiently soft for pressing into the rough shape of prisms or lenses to be produced. These shapes are known as the blanks and are heat treated under controlled conditions to ensure that the refractive index and the dispersing quality of the glass satisfy the rigid requirements. Finally, the blanks are ground to the required size and polished (Fig. 2.17). Nowadays optical glass is also produced in small tank furnaces. In ordinary tank furnaces the glass attacks the refractory material and picks up impurities from it. To avoid this, the tank is lined with a layer of platinum metal which is not easily affected by glass. This method is however employed only when large production is required.

FIGURE 2.16 *A glowing refractory pot containing optical glass is being taken out of the furnace.*



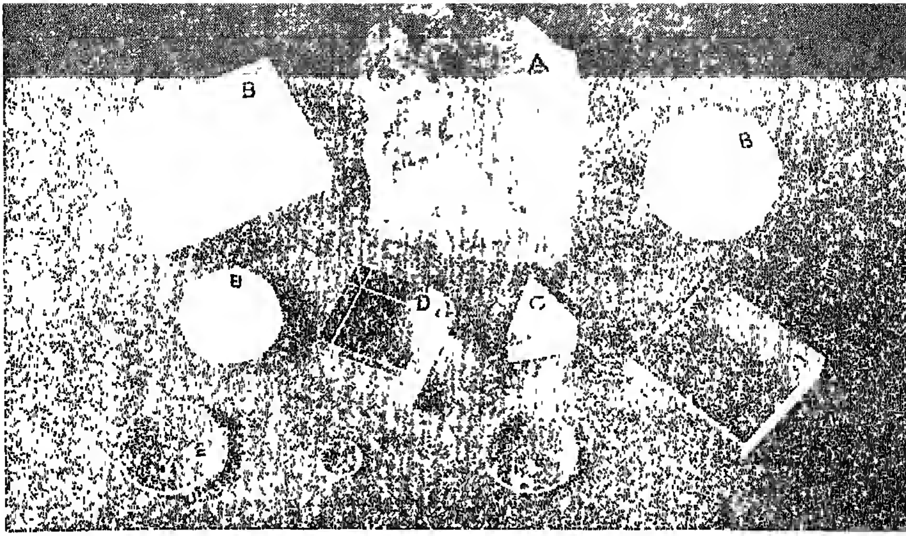


FIGURE 2.17 *Optical glass products made at the Central Glass and Ceramic Research Institute: (a) chunk of optical glass broken out of the pot, (b) ground blanks, (c) polished prism, (d) blocks and (e) lenses*

Annealing: We have seen how different shapes are made of glass by blowing, pressing, drawing, rolling, etc. The articles having a thin wall such as bulbs, tubings, fibres, etc. cool down to the rigid state very rapidly. However, comparatively thicker articles such as bottles, pressed wares, plate glass, etc remain almost red hot when they come out of the forming machines. The outer layer of these glass articles gives out heat to the surrounding cold air and becomes hard. Compared to metals, glass conducts heat very slowly and as a result, the inside of the glass remains much hotter than the outside surface. Later, when the hot and soft glass inside the wall cools, it tends to contract ; but the glass near the surface, which is already cold and rigid tends to resist contraction. As a result of the uneven cooling of the articles, the glass becomes weak and it breaks easily. To avoid this, articles coming out of the forming machines are not allowed to cool in the

open-air; instead, they are slowly cooled under controlled conditions in a furnace and the process is known as 'annealing'. In Chapter 4 we shall examine in greater detail why the strength of glass depends on the rate of cooling from the soft state. In modern glass practice the furnaces used for annealing are of continuous type. To anneal glass containers, they are placed on a continuous belt of wire mesh which carries the articles into the furnace at a slow and controlled speed (Fig 2.18). Inside the furnace they remain within a suitable temperature range so that the weakness of glass due to unequal cooling is avoided. As they move further down the furnace the annealed articles are cooled slowly to room temperature (Fig. 2.19). Finally they are sorted and packed. Normally, it takes half-an-hour to two hours for the articles to pass through the annealing furnace, depending on the shape and size of the objects. Thicker and larger articles have to be cooled more slowly and they take longer annealing time.

During the process of annealing small but significant changes occur in some of the physical properties of glass parti-

FIGURE 2.18 *Glass containers stacked in annealing lehr*

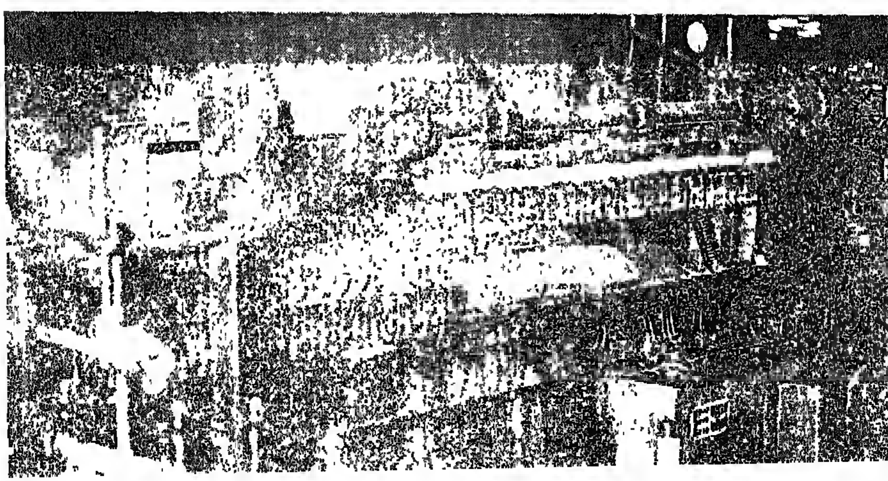


FIGURE 2.19 *Glass containers coming out of the annealing lehr*

cularly in the optical properties. Such small changes are of no consequence in the ordinary varieties of glass. But they are very important in optical glass. The optical glass blanks are, therefore, annealed under closely controlled conditions, sometimes for hundreds of hours, so that every time the same optical properties can be obtained.

Crystals in glass: It was mentioned in the beginning that on cooling a liquid, through the crystallisation temperature, solid crystals appear. There are, however, some liquids which can easily be cooled through this temperature range to rigid glass without any crystal formation This happens because crystals do not appear in these materials unless they are held within the

crystallisation temperature range for a very long time. The actual time required for development of crystals in the common glass forming liquids may vary from a few minutes to several days, depending on the composition of glass and various other factors. For example, in a soda-lime-silica glass if the lime content is increased the crystals would appear more readily. Appearance of the crystals not only makes the glass hazy but also renders it mechanically weak and this defect in glass in known as 'devitrification'. The glass makers are aware of these facts and they control the glass composition and the working temperatures in such a way that the crystals do not appear.

There are, however, certain types of glasses in which crystals are purposely allowed to develop in order to obtain a translucent or completely opaque glass. To this end, certain ingredients such as calcium fluoride, calcium phosphate and tin dioxide are added to the glass batch. They get dissolved in molten glass at high temperatures to form a clear liquid. On cooling the liquid these ingredients precipitate throughout the mass of glass in the form of small crystals and make the glass opaque. This type of glass is known as 'opal' glass. A typical composition used at the back of a clinical thermometer is shown in Table 2.2. The enamel coatings given on metal or glass surfaces are also essentially opal glass melting at comparatively low temperature.

Crystals of tin dioxide, calcium fluoride, etc., are white. There are also certain ingredients which produce coloured crystals and are used for making coloured glass. As discussed earlier in this chapter, oxides of iron, cobalt, manganese, etc., get completely dissolved in glass and the colours produced by these ingredients are clearly visible on cooling the glass. Unlike these 'solution' colours, those due to crystals of gold, silver, copper

oxide, zinc and cadmium selenides, etc., are not fully developed after the glass is shaped and annealed down to room temperature. At this stage the glass remains light coloured; it is again heat treated at or around the annealing temperature for a sufficient period of time, and it is only then that the coloured crystals develop and the glass becomes fully coloured. This phenomenon is known as 'striking' of colour and is characteristic of almost all the colours produced by crystals.

During the fifties a very important development took place in this field when materials having very unusual electrical, mechanical and thermal properties were obtained by crystallising certain special types of glasses under controlled conditions. In these glasses extremely tiny crystal nuclei are first allowed to develop around annealing temperatures. When the glass is further heated to a higher temperature crystals start growing on these nuclei. The process is similar to the 'striking' of colour mentioned in the last para. The essential difference is that in coloured glasses only a small amount of the coloured crystals is sufficient to produce the desired effect whereas, in these materials the major glass constituents such as silica, alumina, etc. come out of the glass composition as crystalline compounds. Because of their crystalline nature this family of crystalline materials made from glass are known as "glass-ceramics". As seen earlier in this section, when glass is devitrified it usually becomes weak due to the presence of comparatively large crystals, irregularly distributed in the glass. Unlike devitrified glass, glass-ceramics contain uniformly distributed crystals, which are so small that normally they may not be visible under optical microscopes. As a result of this controlled crystallisation the material develops very high strength. Some of the compositions also have extremely low thermal expansion

and can stand sudden changes in temperature. Domestic cooking ware and various other articles of common utility are made of these crystallised glasses. Another interesting use of this exceptionally strong material is in the making of 'nose cone' or radome of the missiles. Glass-ceramics having unusual electrical and thermal properties are also finding interesting uses in various other fields, some of which we shall have occasion to look into later in this book.

3

Glass and Light

THE SUN AND A CANDLE

The glorious Sun: For all the energy which keeps things going on this planet of ours, we are indebted to the sun. It is a star having a diameter of about 1.4 million km and temperatures around 4,000°C near the surface. Inside the sun, the temperature has been estimated to be as high as several million degrees. Under this tremendous heat and extremely high pressure the hydrogen gas inside the star is being converted to helium. The net result of this process is that matter is being continuously transformed to energy. The energy thus produced is radiated all round in space in the form of electromagnetic waves, which travel practically in straight lines at a fantastic speed of 10^8 metres per second.

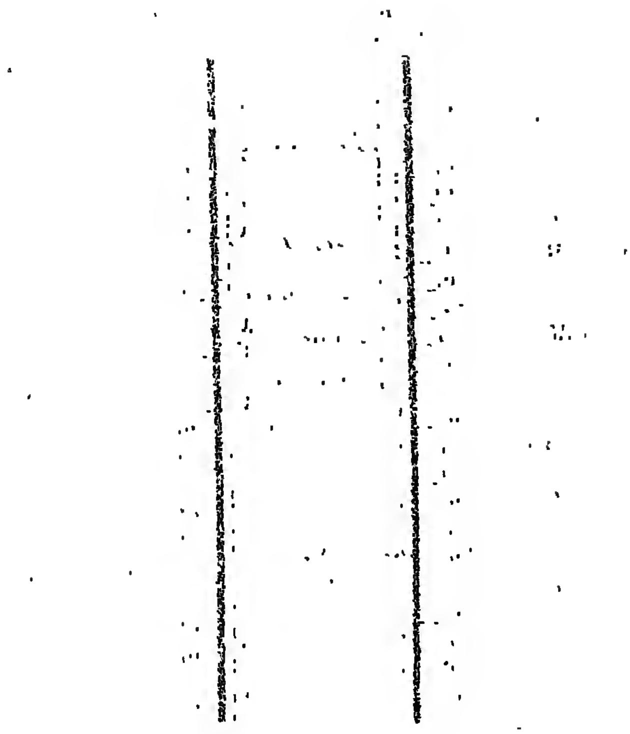


FIGURE 3.1 *The spectrum of radiations*

All the waves of the radiant energy are not, however, of the same length.* The shortest ones have wave lengths around 0.01×10^{-8} cm or 0.01 Angstrom (Angstrom unit $= 10^{-8}$ cm) and the longer waves may be several metres long. As shown in Figure 3.1, solar radiations are classified under different names

* The length of a wave may be measured as the distance between the two successive crests or troughs of the wave.

according to their wave lengths. The shorter the wave length of a radiation, the higher is the energy. The γ-rays and x-rays have the shortest wave length and therefore the highest energy, whereas, the long radio waves used for wireless communication have the lowest energy.

Sunlight is a mixture of radiation having all these wave lengths. Of the radiations emitted by the Sun those visible to our eyes have wave lengths ranging only from 4,000 to 7,000 Angstrom. These light radiations of different wave lengths have different colours. For instance, the shortest waves (around 4,000 Angstrom) are violet and as the wave length increases the colour progressively changes to indigo, blue, green, yellow, orange and finally to red. The red colour is, therefore, due to the radiations having the longest wave length, (around 7,000 Angstrom) in the visible region. The radiations shorter than 4,000 Angstrom or longer than 7,000 Angstrom cannot be seen by the human eye and these invisible radiations are known as the ultra-violet and infra-red rays, respectively. We shall now consider how the visible light, as well as the ultra-violet and infra-red rays, are produced and the ways in which they interact with glass.

Lamps: As the Sun goes down darkness sets in and man has to look for some artificial light source. The first artificial light that primitive man could produce came from fire. The next development was the lamp which has been used from prehistoric times to produce light by burning vegetable oils or animal fats. Later, by the end of the last century use of kerosene came into vogue. These lamps used to be made of stone, earthenware, metals and also glass. We have already come across the use of glass for making beautiful Mosque lamps in medieval Egypt. Even in the present times use is still being made of glass for making chimneys to pro-

tect the flame from wind gusts and avoid smoke and flickering. Some quantities of glass chimneys are still being produced in our country mostly for rural areas.

An important break-through in this field came in the year 1879 with the invention of the electric incandescent lamp by an American scientist named Thomas Edison. Inside an incandescent lamp there is usually a thin filament of tungsten metal which is heated to temperatures above 2,000°c by passing electric current through the wire and as a result, it glows The reason for using a tungsten filament is that its melting temperature is much higher than that of most of the common metals. Sometimes filaments of carbon are also used for a similar reason. The metal does not burn up because it is encased in a glass shell which is either evacuated or filled with an inert gas such as argon. In gas filled lamps the nature of the gas and its amount are so selected that the glow of the filament becomes maximum.

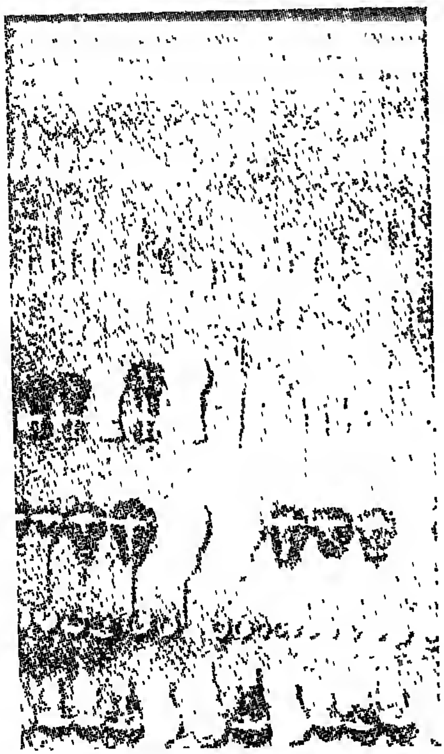


FIGURE 3.2. *Components of incandescent electric lamps*

The photograph in Figure 3.2 shows the different components

of a typical incandescent lamp. It is apparent that glass plays an important part in the production of an incandescent lamp. First, there is the lamp shell, generally made of common soda-lime-silica glass. Sometimes small amounts of lead oxide and other minor ingredients are also added for easier melting and better working properties. The shell may be transparent or 'frosted' by etching usually with some fluorine compounds, in order to mask the glare of white hot filament by diffusing the light. In the so-called 'daylight' lamps the shells are made of bluish-green glass which absorbs the yellow and red portions of the emitted radiation and as a result, the transmitted light appears to be closer to daylight. In some of the special lamps the shells are given a thin metallic coating at the back for better reflection. Laquers, enamels, etc., are also used to produce various decorative effects. The other important glass components are the pillars supporting the lead in wires to which the filaments are connected. Generally, these are made of a special lead glass, which acts as a good electrical insulator and seals well with the metal components. The dark filling material at the back of the bulb is also a special type of glass which acts as an insulator separating the live terminals at the centre from the cap. This glass should soften at comparatively lower temperatures so that the cap can be filled with soft glass without getting damaged due to excessive heat.

Today, incandescent lamps of numerous designs and shapes are being produced for use in homes, streets, factories, automobiles, lighthouses, etc. The most common varieties are those consuming 40 to 100 watts of electrical energy.* The smallest ones are probably the so-called 'grain of wheat' lamps used in child

* A watt is the unit of electrical energy obtained by multiplying the flow rate of electricity (i.e. current in amperes) with the electrical pressure (i.e. voltage in volts).

surgery for illuminating internal organs. It is only about 0.7 millimetre in diameter and 8 millimetre long, consuming only 0.17 watts per hour. One of the largest lamps ever built is about 500 millimetre in diameter and over 1000 millimetre in height and consumes as much as 75,000 watts per hour. It has been reported that still bigger and brighter lamps have been developed in the Soviet Union.

Discharge lamps: These lamps are of a separate variety working on an entirely different principle. In these, there are no glowing filaments, instead there are two metal electrodes sealed in a tube or shell made of glass. Normally, when the electrodes are connected to a voltage source, no current will pass through the air gap because air does not conduct electricity unless, of course, the voltage is extremely high. If, however, the air is drawn out from the glass tube, the pressure decreases and the current starts flowing across the tube at a much lower voltage. This is known as the low pressure discharge phenomenon. As the stream of electrons runs across the tube from one electrode to the other under applied electrical pressure, the electrons hit the atoms of the gas still left inside the tube. The bombarded atoms absorb the energy of the electron and get 'excited' but only for a short time; soon they 'relax' and during this process of relaxation they give out the additional energy received from the electrons, in the form of radiations. The wave length of these radiations depends primarily on the nature of the atoms involved. For example, if a small amount of mercury is introduced in an evacuated discharge tube, then the excited mercury atom will emit ultra-violet and bluish-white light; under more or less similar circumstances sodium vapour would produce yellow light, argon would give red light, and so on.

Of all these types, the use of the mercury vapour lamp is

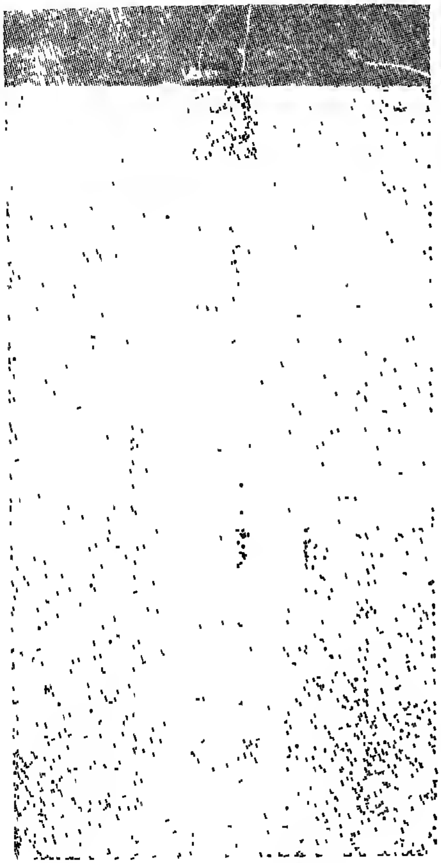


FIGURE 3.3 *Mercury vapour lamp*

more common as a powerful source of visible light. A mercury lamp (Fig. 3.3) consists of an evacuated inner tube or 'arc tube' made of special glass that can stand the heat generated during discharge and can produce a good seal with the metal leads connecting the electrodes. Silica glass or aluminosilicate glasses having high softening temperature are commonly used for the purpose. The arc tube is protected by an outer glass shell made of common soda-lime-silica glass or sometimes, of a heat resistant glass. The lamps are made of different sizes, with power ratings generally ranging from 100 to 3,000 watts. The advantages of mercury vapour lamps over incandescent lamps are that they are more compact and produce more light per unit of electrical energy consumed. They are widely used for illuminating factories, streets and other public places.

In addition to the visible rays, mercury vapour also gives out ultra-violet radiations. It emits strongly the ultra-violet rays of

the wave length 2537 Angstrom which readily kill disease producing bacteria. Because of this useful property of ultra-violet rays, the ultra-violet lamps are used for sterilization of water, processing blood plasma, drugs, etc., in hospitals and factories. Ultra-violet rays also induce various types of chemical reactions and the lamps are used for photo-chemical purposes in chemical industries. Ultra-violet rays are, however, injurious to the eye and skin and therefore ultra-violet lamps have to be used with caution. The arc tube of an ultra-violet lamp is usually made of silica glass. In spite of its much higher cost silica glass is used because an ordinary soda-glass or aluminosilicate glass would absorb much of the ultra-violet rays and therefore would impair the performance-efficiency of the lamp.

Instead of mercury when sodium vapour is introduced in the discharge tube it strongly emits a yellow light. Although a yellow light is by no means suitable for viewing objects in their true colours, the amount of light produced per watt of energy is very high and it gives excellent visibility at night. For these reasons the sodium vapour lamps are used mostly for street lighting.

The other important group of discharge light lamps is the so-called 'Neon-tubes' widely used for advertisements and light signs. In these, neon as well as argon, helium, mercury, etc., are used to produce light of various colours. Neon produces a red glow, helium emits yellow, while blue light is given by a mixture of argon and mercury. A lead or a soda lime glass tube is first bent to the desired shape and sealed at both ends with two metal wires in it. Air is evacuated from the tube and a small amount of the gas is let in at a low pressure. When a high voltage is applied across the electrodes, a stream of electrons passes through the tube and excites the gas to glow.

Fluorescent tube: When the ultra-violet rays fall on certain chemicals they absorb the radiant energy and re-emit it in the form of visible light. This phenomenon, known as fluorescence, has been utilised for producing light. The common fluorescent lamp is made of an evacuated soda-glass tube containing a drop of mercury and a small amount of argon gas. On the inner wall of the tube there is a coating of fluorescent material, known as 'phosphor'. When electric discharge passes through the tube the mercury vapour emits ultra-violet (as well as visible) radiations. The fluorescent material absorbs these ultra-violet rays and strongly emits visible rays.

The fluorescent lamp has several advantages over the conventional type of incandescent lamps mentioned earlier. A fluorescent lamp would produce much more light than an incadescent lamp consuming the same energy. Also, the colour of the fluorescent light can be changed by using various types of phosphor material. For instance, in a 'daylight tube' the quality of the phosphor used is such that the fluorescent light is practically of the same colour as natural daylight. Lamps producing various other colours are also available. In view of these advantages fluorescent lamps of various designs are being increasingly used to replace the older type of incandescent lamps in houses, factories, shops, offices, etc. Although fluorescent lamps were first introduced in the market in the early thirties, their extensive use was a later development. This was largely due to the technical difficulties in producing the right types of phosphor material, whose exact compositions are still considered as closely guarded secrets. Generally, the phosphor material used in a common fluorescent lamp is a mixture of calcium phosphate, calcium fluoride (Apatite) and traces of manganous oxide.

Looking through glass: Among the agencies through which we keep our contact with the world around us, the most important one is light. If we place a plane mirror against the path of a beam of light, the rays will bounce back, like a rubber ball, at an angle equal to the angle of striking the mirror. This phenomenon is called the reflection of light. When the reflected light reaches our eye we see the image through the looking-glass. Certain materials such as water or clear glass offer hardly any hindrance to the path of light and we can see directly through such media. These materials are said to be transparent to light. Ever since the discovery of 'Crystallo' by the early Venetians (Chapter 1, Page 11), this transparent and hard material has attracted the attention of man in devising a variety of equipment through which we can see something more than with our naked eyes. But, before we can go further into the subject it is necessary to understand in a little more detail what happens when light passes through glass.

Bending of light rays: If we partly immerse a rod in water, it appears to be bent from the surface of the water. This is because when light passes from air to water or any other transparent medium its direction changes and the phenomenon is known as the refraction of light. The extent to which the rays are bent is measured by the numerical quantity, the refractive index.

$$\text{Refractive index} = \frac{\text{Sine (angle of incidence)}}{\text{Sine (angle of emergence)}}$$

For air, refractive index is 1.0, which means that there is hardly any change of direction when light passes from vaccum to air. For water it is 1.33, and for ordinary soda-glass the value is about 1.5. The higher the refractive index, the greater is the bending of light. The refractive index of glass can be controlled by changing the composition of glass; for instance by incorporating the oxides of

heavy metals, such as barium, lead, etc., the value can be increased to 2.5 or even more.

When light enters a plate of glass its direction changes due to refraction but as it comes out of the glass through the other surface there is an equal but opposite change in the direction and therefore the glass plate does not have any resultant effect on the direction of light. It remains the same as before. The situation would have been different had the two surfaces not been flat and parallel. If we look carefully through a window glass we may notice small distortions in the object because the surfaces of a common window glass are not always parallel. There are wavy imperfections which slightly bend the light and the objects seen through the glass look deformed. In order to change the direction of light, pieces of glass having one or both the surfaces curved are used. These are called lenses (Figures 3.4 & 3.5). When a parallel beam of light passes through a lens having a convex surface, the rays converge to a point, which is known as the focal point. The rays

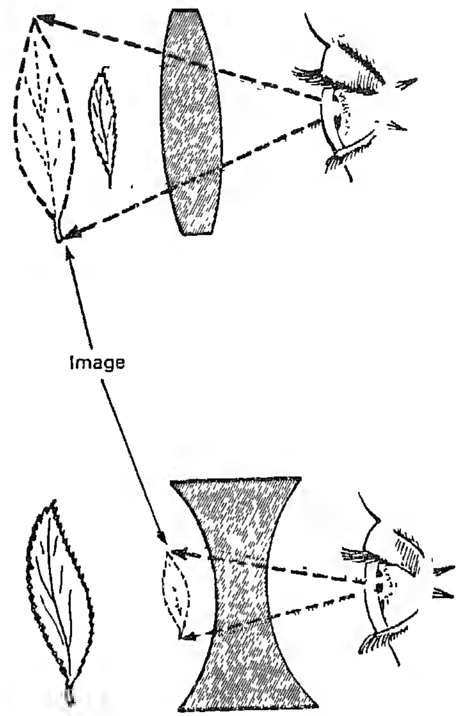


FIGURE 3.4 *Bending of white light by a convex lens*

FIGURE 3.5 *Bending of white light by a concave lens*

coming from a very distant object, such as the sun, are parallel. When all the light and heat energy falling on the surface of the lens is converged at the focus we get a very bright and hot spot. If any inflammable material such as a piece of paper is placed at the hot spot it would catch fire. A lens having a concave surface, on the other hand, has the opposite effect of diverging or spreading out the parallel rays of light. The extent to which a lens would bend the path of light would depend on its curvature and the refractive index. Lenses made of optically homogeneous glass and having accurately controlled refractive indices and curvature are the vitally important components used for making microscopes, telescopes, cameras and various other optical instruments, some of which are described later in this chapter.

So far, we have only considered the passage of white light through lenses and plates. If a parallel beam of white light is allowed to pass through a glass prism and the transmitted light falls on a white screen we will notice different colours ranging from violet to red (Figure 3 6). As we have seen before, white light consists of radiations having all the colours, i e. having wavelengths ranging from about 4,000 to 7,000 Angstrom. The function of the prism is to separate out the radiations of different colours. The reason why the rays are split by a glass prism is that the rays of different wave lengths are not bent to the same extent when they enter and emerge from a prism. In other words, the refractive indices are not the same for all the colours, instead, they decrease with the increasing wave length of the radiations. Thus, the violet rays having the shortest wave length are bent the most, while the red rays are the least bent. This phenomenon of splitting of white light into its constituent colours is known as the 'dispersion of light'.

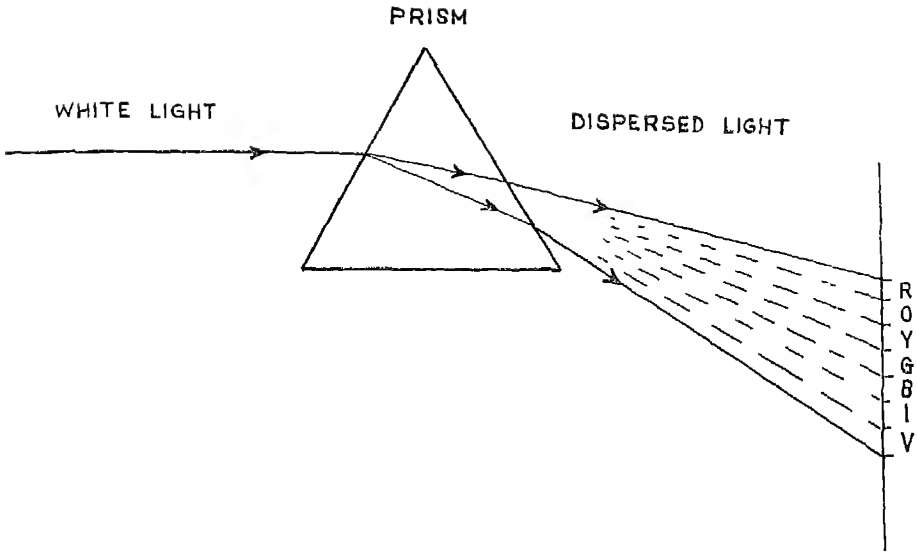


FIGURE 3.6 *Dispersion of light by a prism*

The lenses used in optical instruments for converging or diverging the rays of light also act as prisms and because of this prism effect there is a small but noticeable dispersion of light by the lenses. As a result, the object seen through the lenses look coloured at the edges. This undesirable effect is known as chromatic aberration and is avoided by using a combination of lenses instead of just one lens. The simplest of such combinations consist of two lenses, one made of crown glass and the other of flint glass. Table 2.1 shows that the flint glass contains substantial amounts of heavy lead oxide and therefore its refractive index is higher than that of crown glass; but these two glasses happen to have the same dispersing power. When a concave and a convex lens made of these two glasses are put together the undesirable dis-

persion of light by one of the two lenses is exactly balanced by the other. However, since their refractive indices are different, the bending of rays by one will not be compensated by the other and as a result, we can get the desired convergence or divergence of light without any dispersion. Such a combination of lenses is known as the 'achromatic combination'. The refractive index and dispersion of glass can be changed by changing the composition of glass. There is a large variety of glass compositions with many unusual constituents such as rare earths, phosphates, fluorides, etc., which have various combinations of refractive index and dispersing power. These glasses have been developed in order to meet the demand of the designers of better and newer types of optical instruments.

Optical instruments: Probably the most common use of glass for optical purposes is in the making of spectacles. It has been reported that the Roman Emperor Nero used a large lens, made of a transparent emerald, when he wished to see distant objects more clearly. The ancient Chinese also used transparent minerals for a similar purpose. These crude but highly expensive implements are the forerunners of modern spectacle glasses.

The light rays with which we see external objects are focussed by a convex lens in our eye on the retina at the back of the eye. The light energy falling on the retina creates the sensation of 'vision' through a series of extremely complex processes. For one reason or the other, the lens in the eye may not be able to focus the light properly on the retina and in such a case external objects would appear to be indistinct. This difficulty can be conveniently overcome by putting a glass lens of appropriate shape in front of the eye so that the light rays before reaching the eye will be converged or diverged by the glass lens to an extent just sufficient to

correct the defect of the eye lens.

In some of the spectacles two lenses are used instead of one. One of these is a concave lens, for the distant vision, and the other one is a convex lens for close vision. This type of glasses, known as 'bifocal' lens, was first devised by Benjamin Franklin, a famous American inventor of the eighteenth century. A more sophisticated version of spectacle glasses are the contact glasses which are put right in contact with the eyes. This type of lens can be used by those who do not wish to use the spectacle frames.

The spectacle glasses are generally made of the usual soda-lime-silica composition. Sometimes various colouring ingredients such as cerium oxide, cobalt oxide, iron oxide, etc. are added to cut off the undesirable heat rays, ultra-violet radiation and the glare of bright daylight. This subject of absorption of different rays by glass will be discussed in further detail in the next section.

Telescope: It is generally believed that the basic principle of the telescope was first discovered around 1600 AD by two brothers Zacharians and Johann Jansen of Denmark who were opticians by profession. Looking through two magnifying glasses (convex lenses) they observed that if the two lenses are placed at a certain distance, one can clearly see distant objects as if they are brought much closer. The optical principle of this observation is explained diagrammatically in Figure 3.7. The first lens called the 'objective' brings into focus a bright and inverted image of the distant object. The light rays coming from a distant object are practically parallel and the parallel rays falling on the convex lens converge on a plane called the 'focal plane' of the lens. This image is then magnified by a second lens called the eye piece. The eye piece acts as a simple magnifying glass enlarging the bright image. The famous Italian astronomer Galileo utilised this principle and made

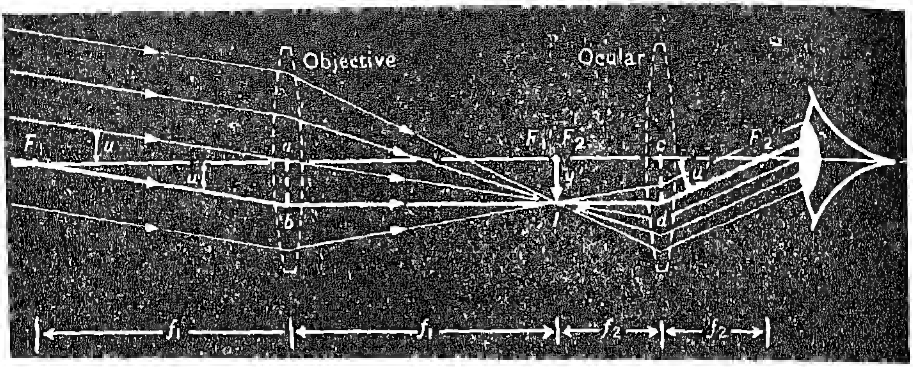


FIGURE 3.7 *Optical principle of an astronomical telescope*

a simple telescope by putting two convex lenses in an organ pipe. He obtained a magnification of about 30 times and looking at the sky through the telescope he could observe mountains on the surface of the moon and distinguish some of the stars in the milky way. Modern telescopes are, however, far more complicated in optical design using achromatic combinations of lenses and various other refinements to get clearer images of distant objects. Telescopes are used in various instruments used for surveying and scientific studies. The binoculars (Figure 3.8) we sometimes use to see distant objects are, in principle, a twin telescope. For astronomical studies, however, large telescopes having high magnifying and light-gathering power are used.

The magnifying power of a telescope is the ratio of the focal length of the objective and the eye piece. The larger the focal length of the objective lens and/or the smaller the focal length of the eye piece, the greater is the magnification. The larger the surface of the objective lens, the more light it can gather to produce a brighter image. However, there is a limit to which its size can

FIGURE 3.8 *Optical principle of a binocular*

be increased due to various practical difficulties including the problem of accurately correcting the chromatic aberration of the lenses.

A solution to this problem was obtained by using a concave mirror instead of a convex lens as the objective which gathers the light falling on its surface from distant objects and by reflection focuses it before the eye piece. The reflecting telescope, as it is called, was first made by Issac Newton. One of the largest optical

telescopes in the world is the reflecting telescope at the Mt. Palomer Observatory in California, U.S.A. It has a huge glass reflector, of about 5 metre diameter, made at the Corning Glass Works in New York. The shape was made by pouring some 20 tons of molten glass in a sand mould and then slowly cooling it under controlled conditions (annealed) in about one year. Due to the tremendous light gathering power of the giant mirror one can see the stars at distances of millions of light years. [Light years is the distance covered by light in one year travelling at a speed of 10^3 metres per sec. It works out to be nearly 1.8×10^{13} km.]

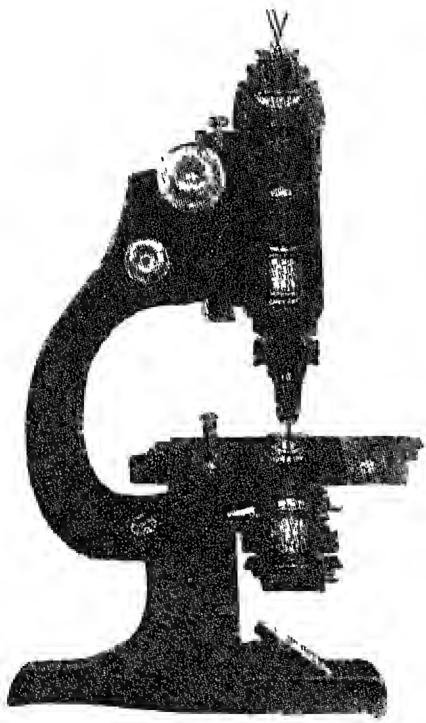


FIGURE 3.9 *Optical principle of a compound microscope*

Microscope: The simplest of the microscopes is the magnifying glass. When the light from an object passes through this convex lens, the object seen through the glass appears to be larger and nearer. The magnifying power of a convex lens was known from ancient times and was utilized as reading glass and later in spectacles. The discovery of the principle of a modern compound microscope is due to the Janson brothers who had first invented the telescope. The basic principle of a compound microscope has been illustrated in Figure 3.9.

We have seen that in telescopes, the faint light from distant objects is gathered by a large convex lens (the objective) or a concave mirror and focussed to form a bright image. This image is subsequently enlarged by the magnifying lens called the eye piece. Here, the purpose is to enlarge a small object which is at a close distance. It is important to realise that when the object is magnified the amount of light coming from the small object spreads out over a much larger area of the magnified image. It is, therefore, necessary to make the object very bright and this is done by focussing a beam of light with a condensing lens. From the object to be magnified the light spreads out. The diverging beam then passes through a convex lens and is brought to focus to form a magnified image. This is further magnified by the second convex lens, the eye piece

The magnifying power of a microscope depends on the focal lengths of the two lenses, the objective and the eye piece as also on the distance between the two lenses. The larger the distance the greater is the magnifying power. In modern optical microscopes magnification upto about 2,000 times has been achieved by using an appropriate combination of lenses and other optical refinements.

The efficiency of a microscope or a telescope depends not so much on the magnification as on the resolution of the image. For instance, when a cluster of stars millions of light years away are observed, the important point is the resolution of the individual stars even if they would appear as the tiniest dots rather than to get a diffused image that would look like a large blob of stellar mass. To achieve this, the glass will have to be of the very highest quality with precise optical properties. Indeed, it is a challenge to the art of glass-making which has been met with admirable success. But even with the best of lenses, one cannot achieve very high resolution from a microscope or telescope just by using only

a single objective and one eye piece. This is because of the aberrations of the image due to the inherent limitations of the shape of a lens. We have already mentioned the chromatic aberration of a lens which makes the object coloured at the periphery. There is also a second type of aberration known as spherical aberration, which produces the same undesirable effect, and has to be overcome to obtain a clear image. The important breakthrough in this respect was made by the German physicist, Otto Schott, who showed that by using appropriate combinations of lenses of crown and flint glass both these aberrations can be avoided. Thanks to this most significant discovery, modern microscopes and telescopes with an extremely high resolving power have been made. With such improved lenses in modern microscopes we can see the tiny biological cells, the bacelli which spread diseases and can identify the minerals from which various materials of common utility including glass itself are produced. With the glass lenses and mirrors of the giant telescopes scientists probe the vast space and can see objects as far as 10^{18} miles away.

Some of the other important optical equipment are the periscopes used in submarines and tanks, photographic cameras, and the optical lasers, the wonderful light pumping device, which we shall discuss later Another extremely useful optical equipment is the spectrometre used for widely different purposes ranging from crime detection to the study of the chemical constitution of distant stars. All this knowledge, which profoundly influences our life and thoughts, we owe to glass.

Filtering of light : As we discussed earlier in this Chapter, light is a form of energy which travels in the form of waves and the colour of the light depends on the length of the light waves. Although our eyes can distinguish the seven different colours

present in the spectrum namely, violet, indigo, blue, green, yellow, orange and red, the basic colours that our eye can see are only three, namely, blue, green and red. There are, so to say, three messengers in the optic nervous system, one carrying the sensation of blue, one of green and the third of red. 'Seeing' any other colour is the result of addition or substraction of the messages carried by these three messengers. The blue, green and red are, therefore called the 'Primary Colours'. When the red and green are mixed the colour produced is yellow, whereas, red and blue gives pink. Mixed in equal proportions the three primary colours produce white. When all the three colours are completely transmitted through a glass, the glass appears to be colourless and when they are completely absorbed, it would appear black. A coloured glass absorbs the three colours partially and in unequal amounts. For instance, a glass in which a small amount of chromium oxide is dissolved, absorbs substantial amounts of red and blue but transmits most of the green. Therefore, when white light passes through the glass the transmitted light would appear green. A glass containing manganese (in the Mn^{3+} form) would behave in the opposite way; that is, it would absorb more of green and transmit the red and blue and would therefore look pink. We have seen earlier (page 29) that by combining the selenium red and cobalt blue with the green due to iron impurities, a grey shade is obtained and the glass appears to be colourless. Grey is not really a true colour ; it is only a mixture of black and white.

Coloured glass : The first glass that was made by man was coloured because the raw materials used for glass making in ancient times invariably contained various colouring ingredients as impurities. Later when the technique of making colourless glass was developed, the use of coloured glass still continued for their

FIGURE 3.10 (a,b) *Rolling a glass spiral for making bangles*

aesthetic appeal as also for their practical utility. One of the important uses of coloured glass in India is in the making of bangles (Fig. 3.10). In the 'glass-town' of Firozabad in U.P. very large quantities of glass bangles and many other varieties of coloured glass articles are produced.

The use of coloured glass is not by any means restricted to the production of bangles and other artistic glassware. Substantial quantities of glass containers are also produced from glasses coloured amber or green. The coloured containers absorb most of the ultra-violet radiations and a substantial portion of visible light. They are generally used for preservation of certain medicinal preparations, chemicals, beverages, etc. which would otherwise slowly decompose under the influence of ultra-violet radiations

from the sun. Use of coloured glass for containing such light sensitive materials is particularly important in tropical countries like ours where intensity of solar radiation is much higher than that in some of the other parts of the world.

Another important use of coloured glasses is in the making of traffic signals, commonly seen on roads, railways and airports. The colours of these glasses are required to conform to fairly strict specifications so that they can be clearly seen and distinguished from one another from long distances and under adverse weather conditions. Coloured signal glasses are used in the form of lenses of various shapes, so that, the maximum amount of light from the signal source would reach the observer. One of such types is the 'Frensel lens' shown in Figure 3.11. The shape of the lens is such that the light beam coming out from the signal source is concentrated along horizontal planes parallel to the ground so that it can easily be seen by observers standing at or close to these levels. There are also various other shapes of signal lenses used to obtain the required types of light distribution.

Coloured glasses are also used to protect the human eye from excessive glare, heat and ultra-violet radiations. A welder who watches his job through a white hot flame, or an electric arc, has to use heavily coloured glass which should not only cut off the glare of extremely bright light but also should protect the eye from the damaging ultra-violet and heat rays coming from an electric welding arc. There are certain types of welder's goggles which are not permitted to transmit more than 0.00005 per cent of the ultra-violet light. Similarly, those who have to stay out in snows for long periods of time under bright sunshine cannot see properly due to high reflection of light from dazzling white snow. Sometimes, prolonged exposure to excessive glare may even lead to

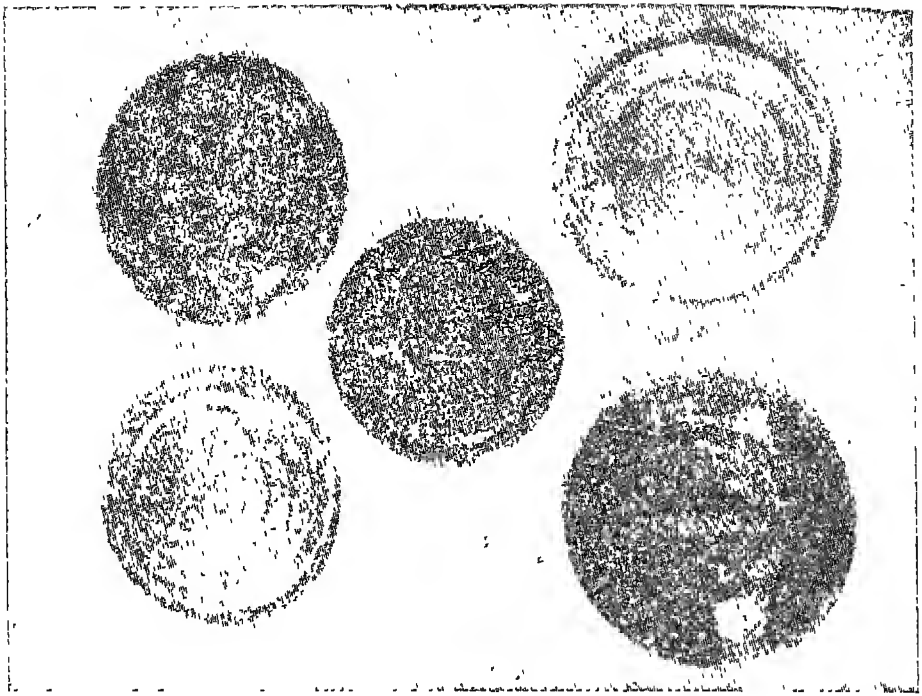


FIGURE 3.11 *Various types of signal glasses*

'snow blindness' unless the eye is protected with coloured snow goggles. Normally, the snow goggles are made almost neutral grey i.e. all the three colours are absorbed almost equally but not completely so that one can see the objects in their true colour.

Another important use of coloured glasses is for 'filtering' certain portions of the light radiations before it is allowed to reach an optical instrument such as a camera. These glasses are called the 'Light filters'. To avoid an undesirable haze in the photographs taken under bright sunshine sometimes a 'Haze filter' is used with

the camera. The glass used in this filter strongly absorbs the invisible ultra-violet radiations. These radiations, present in the sun-light, are scattered by dust particles in the atmosphere and, in addition to the light coming from the object to be photographed, scattered ultra-violet radiations also enter into the camera and produce the undesirable haze. This is avoided by placing an ultra-violet absorbing glass filter in front of the lens. Light filters of other colours are also used to obtain special photographic effects. For instance, a yellow filter would transmit very little of blue from the sky and the sky would look darker compared to the white clouds. As a result, a better contrast between the white clouds and blue sky is obtained in a photograph taken with a yellow filter. For similar reasons the green foliage is made to look darker in a picture by using a red filter.

Glass and ultra-violet radiations : Radiations in the wave-length region, 1000 to 4000A°, are known as the ultra-violet rays (Fig. 3.1). These rays are too short to respond to human eyes but nevertheless play a vitally important role in the chemistry of the life processes. Most of the common sources of light emit certain amounts of ultra-violet radiations and as we noted earlier, the sun rays and the mercury discharge lamps are particularly rich in the ultra-violet radiations.

An ordinary soda-lime-silica or boro-silicate glass would absorb these radiations very considerably and are not, therefore, suitable for making the ultra-violet lamp shells. Vitreous silica is generally used for the purpose in spite of its much higher cost. Comparatively recent studies have revealed that the absorption of the ultra-violet radiations by an ordinary glass is largely (but not entirely) due to the presence of iron and chlorine as impurities. Glasses prepared from specially purified raw materials transmit

much more of the ultra-violet radiations and some of these glasses are now being used for making ultra-violet lamps emitting bactricidal radiations. For absorption of these radiations, glasses are made with ferric oxide or cerium oxide in the composition. These are used in eye protecting glasses, haze filters, etc. some of which were mentioned earlier.

The ultra-violet radiations are known to induce various chemical changes in materials that are otherwise stable. Glasses containing oxides of manganese, vanadium, cerium, etc., when exposed to sunlight, or any other source of ultra-violet radiations, are discoloured due to oxidation or reduction of these constituents. The phenomenon is known as 'solarisation' of glass. Recently, this basic observation has been utilised in developing photosensitive glasses in which it has been possible to reproduce photographic images. The picture to be reproduced is placed on the photo-sensitive glass and exposed to ultra-violet radiations. The exposed glass is then heated under controlled conditions to temperatures below the softening point of glass. These glasses contain small amounts of certain metals such as gold, silver, etc. which are very finely distributed in the glass. On heat treatment, tiny crystals of the metals start growing, but only in those portions of the glass which were exposed to the ultra-violet rays and the characteristic colour due to these metallic crystals develops. The process is more or less the same as that employed for 'striking' colours in glass about which we discussed earlier (p. 57). The essential difference is that in this case the colour strikes only in the exposed portions of the photo-sensitive glass and as a result, a photographic image is reproduced in the glass. The picture in Figure 3.12 is a reproduction in a photo-sensitive glass, developed by the Corning Glass Works of U.S.A.

FIGURE 3.12 *Picture in a photo-sensitive glass*

Another interesting behaviour of some of the photo-sensitive glasses is that the portion of the glass exposed to ultra-violet radiations is chemically more reactive than the unexposed portion. For example, if a wire net is placed on such a glass and irradiated with the ultra-violet rays then the portions of glass exposed to the ultra-violet rays are more readily attacked with hydrofluoric acid. The acid dissolves away the irradiated areas leaving the portions, which were under the shadow of the net, almost unattacked. The result is that an exact replica of the wire net can be reproduced in the glass itself. This ingenious process known as the 'chemical machining' of glass is employed for making special and intricate glass shapes having rigid dimensional specifications. In Figure 3.13 we notice a number of glass articles with various types of perforations made by the chemical machining process.

The heat rays: Just as the radiations shorter than 4000Å (ultra-violet rays) are not visible to our eyes, so are those longer than 7,000 Angstrom or so. These waves are longer than the longest visible rays, namely the red rays and are called the 'infra-red' rays. The heat energy radiated by material bodies are in this wave length region of the spectrum (Figure 3.1). The warmer the

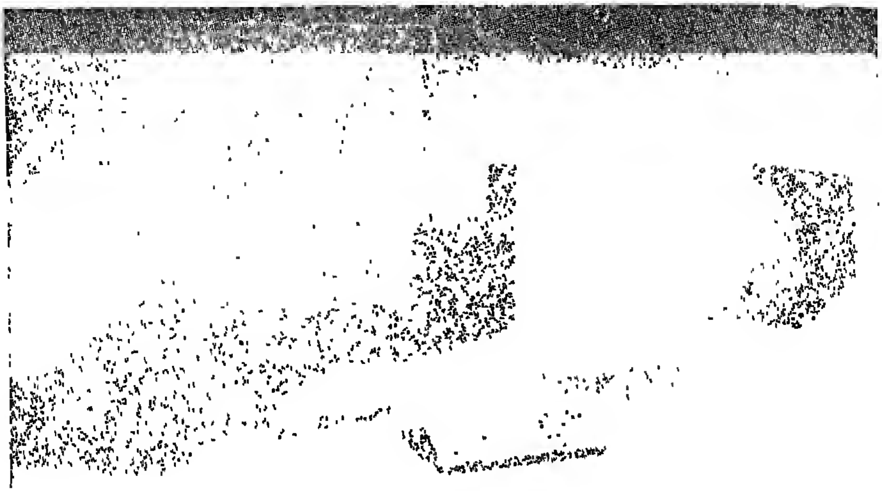


FIGURE 3.13 *Reproducing intricate replica on glass by chemical machining*

body the shorter are the radiated waves. When a body becomes sufficiently hot (around 600°C) the wave lengths of some of the emitted radiations become shorter than 7000 Angstroms and at this point we see the body glowing red hot. On further heating, the glow becomes brighter and the colour progressively changes to orange, yellow and finally to a dazzling bluish white. The radiations emitted by an extremely hot body like the sun are mixtures of the ultra-violet, visible, infra-red and other rays having a wide range of wave lengths. Of these, the infra-red rays produce the sensation of heat. The heat rays from the sun range from shorter wave lengths (around 10,000 Angstrom). On the other hand, most of the heat energy emitted by hot sand on a beach will be of much longer wave length (around 50,000 Angstrom) because the temperature of the sand is very much lower, say 40°C

compared to 4,000°C or so on the surface of the sun.

A soda-lime-silica glass is not only transparent to the visible rays but also to most of the heat rays of wave lengths upto about 20,000 Angstrom. The common glass is, therefore, transparent to the heat rays of the sun but is opaque to the rays emitted by bodies at or around the usual room temperature. On a cold bright day a glass window will allow the heat rays from the sun to come inside the room and warm it up. But it will not permit the long wave heat rays emitted by the warm room to go out. It is like a one-way traffic. This is one of the important reasons why glass is so extensively used for construction of buildings in colder countries. Let us now see how glass can be used to keep a room cool on a hot summer day. Here the first problem is to find a glass that would absorb the short-wave heat rays from the sun. To develop this heat absorbing property, iron oxide is introduced in the glass composition mostly in the 'ferrous' (Fe^{+2}) state. These iron containing glasses not only absorb the short wave heat rays but also absorb substantial amounts of red light and ultra-violet rays and thus they cut off the undesirable glare and the ultra-violet radiations. 'Calorex' is the trade name of one of these types of glasses. When such a glass is put in the window it absorbs the short-wave heat rays from the sun. As a result, it also becomes hot and itself starts emitting heat rays. However, the temperature of the heat absorbing glass being much lower, the emitted rays will be of long wave lengths, mostly longer than 30,000 Angstrom or so. To avoid the entrance of these long wave heat rays inside the room, it will be sufficient to put a second sheet of an ordinary window glass which can absorb most of it.

Although the use of double glazed windows is more expensive, it offers several advantages. At or around the room tempera-

ture much of the heat can flow in or out by conduction through the thin glass wall. This is conveniently avoided by using two glass panes with an insulating air space in between. Double glazing not only prevents the heat from getting in or coming out of the window but also acts as an efficient sound proof barrier to make the building relatively free from noise and vibrations.

So far, we have considered only absorption of the infra-red rays. There are also interesting uses of glasses transmitting these rays. It was mentioned earlier that the red colour in glass is produced due to the presence of small crystals containing complex compounds of cadmium, sulphur, and selenium. These glasses absorb all the blue and green, but transmit a portion of red and much of the infra-red. When the concentration of the colouring crystals is further increased the glass will absorb the red also and will, therefore, appear black. But they would still transmit only the short wave infra-red rays (7,000 to 50,000 Angstroms). These types of black infra-red transmitting glasses are used as 'filters' to send invisible infra-red signals which can be detected by using special electronic devices.

There are also other uses for certain special types of glasses which, unlike an ordinary glass, would transmit long-wave infra-red rays, having wave lengths upto 120,000 Angstroms. On a dark night we cannot see anything because no light comes from the objects around. However, they are still radiating infra-red rays. There are special photographic materials which are sensitive to these invisible heat rays just as an ordinary film is sensitive to the visible light rays. Using such infra-red sensitive films it is possible to take photographs in complete darkness of the objects emitting infra-red rays. But the problem arises in making a camera because an ordinary glass lens would absorb all these infra-red rays.

The problem has been solved by developing special glasses made of unusual materials such as arsenic sulphide, antimony sulphide, etc. With these infra-red transmitting glasses it has been possible to advance the technique of infra-red photography considerably. Methods have also been developed to "see" in complete darkness using electronic and optical devices in which infra-red transmitting glasses are used. These and other similar devices are widely used in various types of defence equipment including tanks, guided missiles, etc.

Many of the technological developments which originally took place to meet specific defence requirements have, at a later period, found very important applications for peaceful purposes. Infra-red photography is a recent example of such cases. The technique is now finding novel uses in industry, agriculture and medicine. For instance, when there is an inflamation in the human body, the affected part becomes slightly warmer than the surrounding area and, therefore, emits comparatively more infra-red radiation. In an infra-red photograph it, therefore, shows up as a brighter area and can easily be detected even in an early stage, when it is not visible to our eye. Similarly, many of the diseases in plants can be detected by infra-red photography much earlier than by any other method so that necessary remedial measures can be taken in time. In short, whenever a change in the system leads to a change in temperature, it can be detected by this technique. Indeed, the method holds considerable promise of furthering our knoweldge in various fields of science and technology.

4

Handle with Care

SO FAR, we have come across quite a few varieties of glasses and shall have occasion to consider many others in the subsequent pages of this volume. In spite of the increasing width of application, one of the important factors which severely limits the use of glass is its fragile nature. In this chapter we shall consider how strong or weak glass is compared to other materials and to what extent it has been possible to improve upon the strength of glass.

When a tumbler slips from a careless hand the glass breaks and the damage is irreparable. This happens because the force of the impact is so high that the glass shape cannot bear it and it yields. There are several ways in which an external force or stress

can be applied on a body. When an iron wire is pulled at the two ends then the stretched wire is said to be under a 'tension' and the applied stress is known as the 'tensile stress'. On the other hand, if a body is pressed from opposite sides it experiences a 'compressive stress'. For example, in a brick wall an individual brick has to bear the load of the other bricks on top of it and therefore, the brick below is under a compressive stress. Apparently, the compressive stress is the opposite of the tensile stress. The deformation of the body caused by applying a stress is known as the 'strain'.

Although stress can be applied on a body in various ways, it is generally believed that a rigid body breaks only under tension. Let us, therefore, examine again in a little greater detail what happens if we stretch a piece of wire by applying increasing amounts of tensile stress. When a load is applied, the wire stretches out but comes back to its original shape as soon as the stress is removed. This reversible change is known as the 'elastic deformation'. The higher the load (stress), the greater is the elongation (strain). In other words, with increasing stress the strain increases and the ratio, stress/strain is known as the modulus of elasticity or Young's Modulus. There is, however, a limit to which the iron wire can be stretched with increasing stress and if further stress is applied then the wire will be permanently deformed and will not come back to its original size even after the load is released. As distinct from the temporary 'elastic deformation', this permanent change in shape is known as the 'plastic deformation'.

In an iron wire the constituent iron atoms are arranged in layers in such a way that under an excessive tensile stress some of the layers can 'slip' on the others and take a set of new positions through a series of complex processes. This permanent displacement of the atomic layers results in plastic deformation. If,

however, certain other elements such as carbon are present in the metal as impurity then these foreign atoms entering between the layers of iron atoms may prevent sliding of the layers. Cast iron, for example, contains large amounts of carbon impurity and that is why it does not show any plastic deformation. Under excessive tensile stress it does not deform but breaks. Such a material which breaks without showing plastic deformation is generally called 'brittle'. A cast iron rod would break under the tensile stress produced by a load of about 1,450 Kg acting over an area of 1 cm^2. This is the tensile strength of cast iron. Similarly, the tensile strength of steel is about 3,600 Kg/cm^2. It may well be asked that compared to cast iron and steel what is the strength of glass? This is a question to which a straightforward answer cannot be given, for reasons we shall presently see.

WEAKNESS OF GLASS

The primary constituent of a common glass is silicon dioxide (SiO_2) or silica. Inside the glass, each of the silicons is hooked to four oxygen on four sides and each of the oxygen is linked to two silicons. So the ratio of Si:O remains 2:4 i.e. 1:2. In this way silicon and oxygen are arranged in a form somewhat analogous to a wire net which is woven not only along the length and breadth but also along the height i.e. in three dimensions. Figure 4.1 gives a diagrammatic view of a two-dimensional network of silicon and oxygen. In such a network structure there is no possibility of plastic deformation as has been seen to occur in crystals of iron metal. Therefore glass will also behave as a brittle material like cast iron. When tensile stress is applied on a glass rod of say 0.6 cm diameter, at first, there will be a small elastic deformation. As more and more stress is applied it will

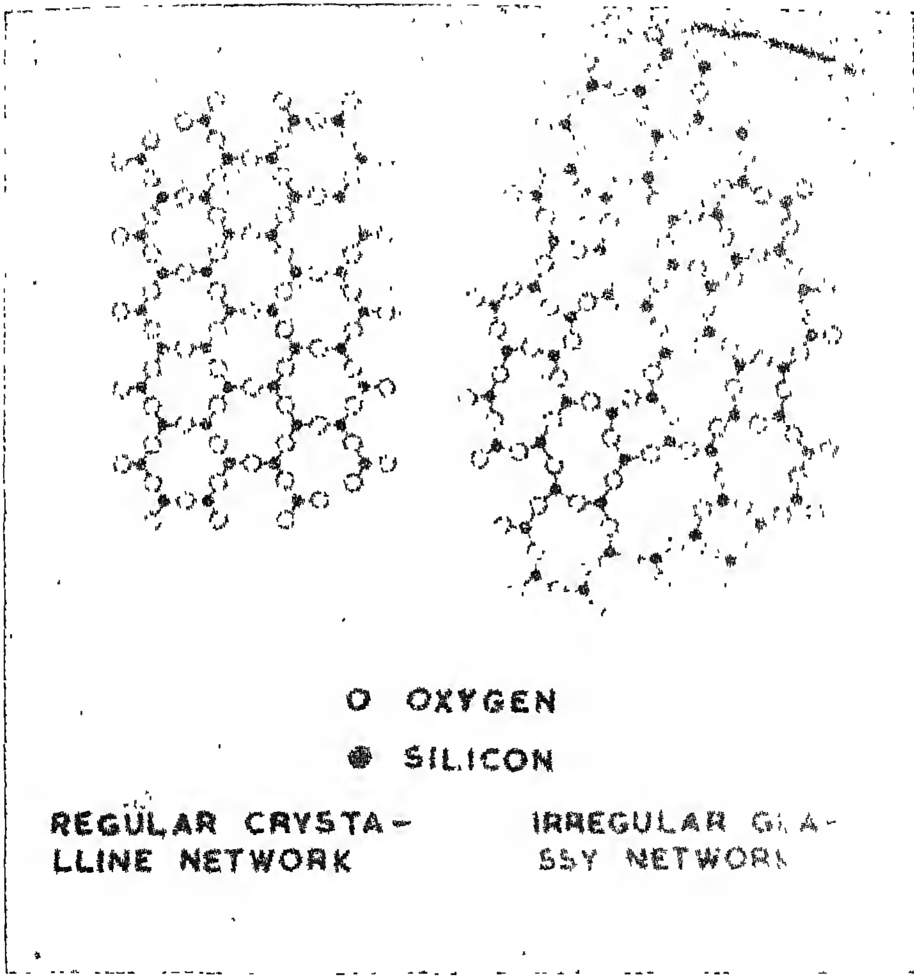


FIGURE 4.1 *Two dimensional network of silicon and oxygen in silica glasss*

progressively increase in length but only upto a limit of 0.01 per cent or so. That is, the length can increase upto ten-thousandth

part of its original length as a result of elastic deformation. If stress is further increased it cannot expand any more to accommodate the stress and to release the excessive stress it will break. The strength with which silicon and oxygen are linked to each other in the network is so high that a stress of 290,000 Kg/cm^2 is required to break the bond. But in practice it is found that the 0 6 cm diameter glass rod breaks at a stress of only about 700 Kg/cm^2. The measured strength of a glass rod is therefore not even one per cent of its intrinsic strength. Why is it so?

The answer to this puzzling question was first given by a scientist named Griffith. We know that it is not easy to tear a cloth by stretching it. Yet when we go to buy a piece of cloth, the salesman first makes a little cut and then easily tears out the measured length. Obviously, this little cut produces a weak spot, at which the strength is low enough to tear it easily. A very similar situation is encountered in glass. Griffith suggested that over the apparently smooth and clear surface of glass there are numerous minute cracks. Some of the cracks are produced when the glass article is shaped by pressing, rolling or otherwise while others are present as scratches, bruise marks, etc. formed during handling of glass while in common use. Minute cracks are also produced even on a clear and polished glass as a result of chemical attack of moisture, etc. on the glass surface.

When a glass rod is subjected to a tensile stress of say 700 Kg/cm^2 the stress at the tip of the flaws will be much higher and in some of them it may be as high as a few hundred thousand Kg/cm^2. It is here that the crack develops and the glass gives way. In effect, each of these flaws is a minute crack which act as 'stress concentrators'. These flaws on the glass surface reduce the strength of glass to a few hundred Kg/cm^2 from the intrinsic strength of

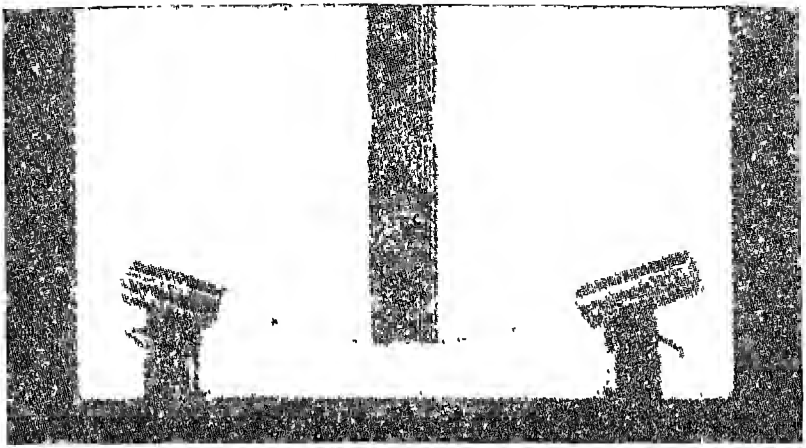


FIGURE 4.2 *Glass rod having an undamaged surface bears a load giving rise to a tensile strength of 10,500 Kg/cm²*.

several hundred thousand Kg/cm², in as much the same way as that a little cut reduces the strength of cloth. Therefore, when we try to measure the strength of glass we only get an estimate of the weakness due to the surface flaws. A freshly drawn glass rod (Figure 4.2) will have only a very few cracks so small that they cannot be seen even under a microscope. On the other hand a rod rubbed with a sand paper will be heavily scratched and its strength may be only ten percent of the strength of a freshly drawn rod. Figure 4.3 shows the size of flaws on a glass surface produced under different conditions and their effect on the average strength of glass.

Variability: If we take a number of apparently identical samples of glass rods and measure their strength it is most likely that the results will vary considerably from sample to sample depending on how deep are the scratches present in the samples. For example, if the average strength of 100 rods is 700 Kg/cm²,

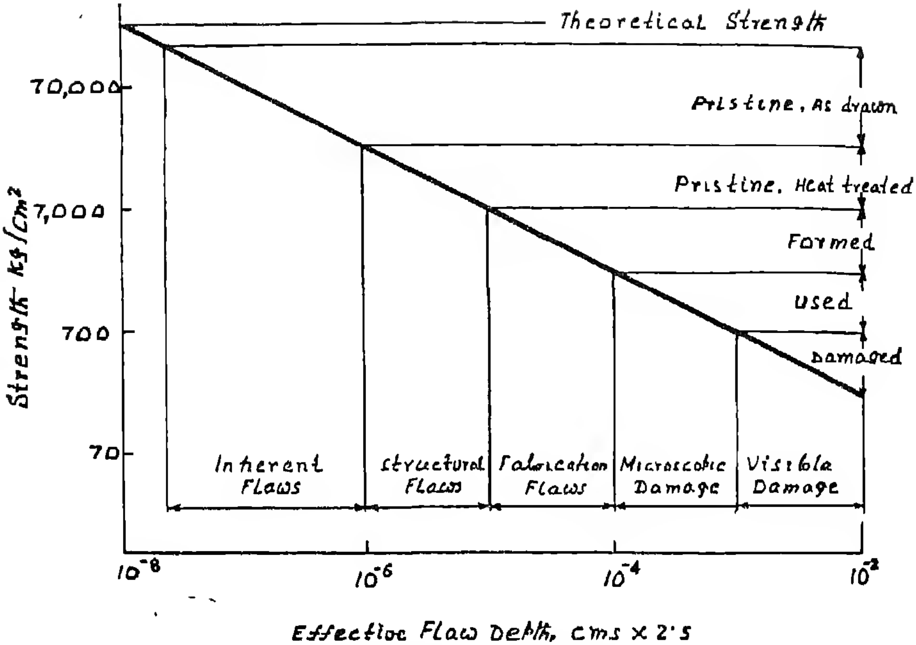


FIGURE 4.3 *Relation between the strength and size of flaws as present in various glass specimens*

the minimum strength may be as low as 300 Kg/cm². Unfortunately, it is the *minimum strength* and not the average strength which matters at the end.

The strength of glass not only depends on the surface condition but also on several other factors and one such factor is the rate at which stress is applied on the glass specimen. The faster the application of stress the higher is the strength. For example, when a glass pane is hit by a stone the stress due to the impact is almost instantaneous. The impact strength of glass may be upto 40 per cent higher than the strength measured by slow

application of load say within a period of a few minutes. On the other hand, if a load is maintained for a long period on a glass it will break at a much lower stress, may be even at less than half the actual measured stress. Therefore, if the minimum breaking stress is 300 Kg/cm^2 the minimum long time breaking stress may be about 150 Kg/cm^2. Taking a safety factor of 2 the value reduces to only 75 Kg/cm^2. The surface of plate glass which has been ground and polished has a larger number of defects introduced during the grinding process. These heavy scratches are not completely eliminated even after polishing and as a result, the strength of a plate glass is even lower than that of a sheet glass produced by any of the drawing processes or by the Pilkington Float Process. (Chapter 2). Sometimes strengths as low as 70 Kg/cm^2 are obtained.

So we see that the presence of surface flaws not only reduces the strength of glass, it also considerably increases the variations in the property from sample to sample. When we have to use glass for architectural or other purposes we cannot afford to presume that the pieces of glass used are of an average strength. It is the minimum strength which has to be considered for design purposes and in the case of glass it is much lower than the average strength. The net result is that the minimum strength that we are likely to encounter in a piece of glass is hardly 0.1 per cent of its intrinsic strength. Can we not make a better use of the tremendous intrinsic strength of glass? In the following section we shall see how far it has been possible to progress towards the ultimate goal of 290,000 Kg/cm^2.

TOWARDS THE ULTIMATE GOAL

The foregoing discussions reveal that glass breaks under a

tensile stress which is very much smaller than its intrinsic strength because of the presence of surface flaws. Therefore, one way of improving the strength will be to get rid of these weak spots from the glass surface, if possible. One of the very few chemicals that 'eats' glass is hydrofluoric acid. In contact with the acid the surface layer of glass is slowly dissolved and the flaws are transformed to rounded pits. Unlike the sharp-edged original flaws these rounded etch pits do not act as stress concentrators. As a result, pieces of glass freshly etched with hydrofluoric acid may show strengths upto several thousand Kg/cm^2 almost approaching the theoretical strength. Although the improvement is highly impressive, it is only temporary. This is because flaws reappear during handling of the glass or even on exposure to normal atmospheric conditions due to chemical attack of moisture, etc. on the surface of glass. Slowly the strength comes down to its original value.

There are various other chemical treatments suggested to improve the strength by removing the surface flaws but most of the methods suffer from the same disadvantages. Attempts have also been made to protect the glass surface with silicones, plastic, etc., immediately after the chemical treatment so that no fresh flaw can appear. However, most of these processes have so far met with limited success due to practical and other limitations. We shall now look into some of the other methods for producing stronger glass, which are fairly well established.

Prince Rupert's drops: If a drop of molten glass is allowed to fall in a bucket of water it will cool instantaneously to a solid tear-shaped drop having a long and thin tail. This quenched glass drop is so hard that it cannot be broken even with fairly hard blows from a hammer. But if the thin tail is broken with a gentle tap the whole drop will break with explosive violence into

numerous pieces. The curious little drop is associated with the name of a Bavarian Prince named Rupert who had probably observed this unusual phenomenon. What was fun for the Prince came to be the basis for development of toughened 'armour plate' glass having a much higher strength than that of ordinary glass.

To toughen a glass plate it is first heated to a temperature at which it just tends to be soft and then the surface is chilled rapidly but uniformly with sudden blasts of cold air. Immediately, the outer surface cools and becomes stiff while the inside still remains hot. Later, as the inner layer of glass cools and contracts it tends to pull in the outer layer which is already hard. As a result of this quenching process, the outer layer of glass remains in a state of compression and the inside under tension.

It was earlier mentioned that glass always breaks under tension which is exactly the opposite to the force of compression developed at the surface of glass after the toughening process. When a tensile stress is applied on a toughened glass, first it has to neutralise the compressive stress already present at the surface and then on application of further stress, a tension appears in the glass. Therefore, the total tensile force required to break a glass having a compressed skin will be much higher. Generally, a toughened plate glass can be four to eight times stronger than an ordinary plate. The improvement in strength is permanent as the flaws present on the glass surface cannot easily penetrate through the comparatively thick compressed layer. When an architect considers the use of a toughened glass he can safely take the minimum working strength to be over 180 Kg/cm^2 after making due allowance for variability and the factor of safety. Compared to this, the corresponding minimum strength of an untreated sheet glass will be around 70 Kg/cm^2. The strength increases further

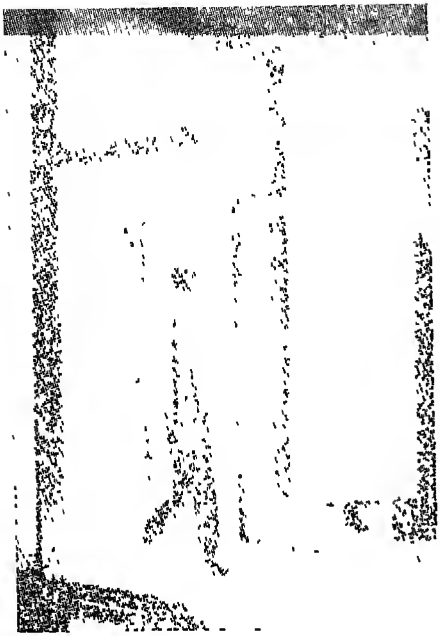


FIGURE 4.4 *Toughened glass door*

when a glass article previously etched with hydrofluoric acid is toughened by the thermal treatment. Toughened glass plates are used for making frameless glass doors (Figure 4.4), glass furniture, etc. In our country and in many other countries the wind shields of motor vehicles are made of toughened glass (Figure 4.5). Various other glass articles such as lenses, tumblers, etc. are also sometimes toughened in order to improve the strength.

In recent years certain processes have been developed which involve chemical treatments of the glass surface in order to obtain a toughened layer. As we have seen earlier (in Chapter 2) one of the important constitutents of glass is sodium. During the process of chemical toughening these sodium ions are extracted from the surface layer and in the sites vacated by sodium, another similar but larger ion, usually potassium ion, is pushed in. The potassium ions are a little too large to fit into the vacant sites and by pushing them in, the surface becomes more compact or compressed. As a result, the strength increases to values as high as 1,000 Kg/cm^2. An interesting feature of chemically strengthened sheets of glass is that they can be considerably bent or twisted like a plastic sheet.

FIGURE 4.5 *Wind shields for automobiles, made of toughened glass*

Because of this feature they are considered to be safer to use in automobiles compared to those toughened by heat treatment. It is expected that future years will see more uses of this type of glass.

Whatever may be the process of strengthening, the basic principle is the same—namely to develop compressive stresses on the surface of glass. If a hollow sphere of glass is put under water, the hydrostatic pressure also produces a uniform compressive stress all around the sphere. The deeper it goes the more it gets compressed and, as a result, the stronger it becomes. Glass spheres

of about the size of a football were developed for carrying instruments and equipment to explore great depths of the ocean. To test the strength of such spheres deep under water, hard pins of steel were fired at the glass ball and the pins were found to break or bend, hardly affecting the surface of the sphere. This experiment clearly illustrates that glass is very strong when its surface is uniformly compressed.

Strength and shape: To break an egg we have to tap it on a hard surface with a fair amount of force. But once the crust is cracked it can easily be peeled off. How is it that the egg shell made of such a weak material is not broken so easily? This is because the shape of the shell is such that when we apply a force to it, the stress is not concentrated at any point; it is more or less distributed throughout the body so that, at no place does the stress reach the breaking limit. This shows that the strength of a body depends not only on the strength of the material with which it is made but also on the shape of the body. The general rule is that the strongest shapes are those which allow the most uniform distribution of stress and as a corollary it follows that the shapes which permit the maximum concentration of stress are the weakest. For example, a hollow sphere of glass will be much stonger than a rectangular shape, because the sharp edges of the rectangle act as 'stress concentrators' and are more vulnerable. These simple facts are of very considerable importance in designing a glass shape, particularly glass containers. A glass container having ridges and other sharp bends for decorative effects is generally weaker than one having a circular and smooth contour. The modern tendency has, therefore, been to produce 'streamlined' contours for better strength and performance efficiency. By proper designing of the containers, it has been possible to reduce the weight of the con-

tainers without affecting the strength. The development of such light weight containers has resulted in reducing the cost of production and transportation.

The strength of glass containers decreases substantially with use because of the scratches that develop during handling, washing, etc. One of the ways to avoid such scratches is to protect the glass surface with a smooth coating of certain transparent materials such as silicones. Coatings of plastic materials are also given for the same purpose. Another interesting process for protection of the surface of glass containers is to give a thin but hard and transparent coating of certain oxides such as titanium dioxide. The containers are sprayed with an organic titanium compound as they come out of the forming machines and in contact with the hot glass surface, the organic compounds burn off leaving a thin coating of titanium dioxide, which adheres firmly to the glass surface. Due to the presence of the hard surface layer, 'titanised' glass containers are not easily scratched during handling, washing, etc. It has been reported that the strength of a freshly formed glass is substantially maintained by such protective surface coatings and breakage losses during handling have been considerably reduced.

Fibre reinforced plastics: We have seen that the strength of glass largely depends on the surface condition and the rate of application of stress. The other important factor determining the strength of glass is the size. The larger the size of the specimen the greater are the chances of the presence of serious flaws and, therefore, the lower is the strength. For similar reasons, the strength of glass rods increases with decreasing diameter. If the average strength of a rod of 0.6 cm dia is 700 Kg/cm^2 then a freshly drawn thin fibre of glass may have strengths as high as 28,000 Kg/cm^2—nearly 40 times higher. This is because the large flaws

which seriously reduce the strength are too large to be present in a thin fibre. Figure 4.2 shows the strength of glass fibres in comparison to other articles of glass.

Although glass fibres cannot be used as such for structural purposes they can be bonded with plastics to form a strong light-weight material. These 'Fibre Reinforced Plastics' (FRP) have very high strength to weight ratio. They can be 50 percent lighter- and yet twice as strong as aluminium. Table 4.1 gives the strength of various materials compared to that of massive glass, glass fibres and the FRP. The other favourable feature of the FRP products is that they are not nearly as brittle as massive glass because of the presence of a plastic matrix. The FRP products are used in construction of buildings, sailing boats, sports cars, aircrafts, space missiles and numerous implements of common utility. It has been predicted that much of the weight of the future missiles and space craft will be due to fibre glass products. The possibilities of their use as reinforcements in cement concrete in place of mild steel rods are also being examined and highly encouraging results are being obtained. Certainly the intrinsic strength of glass is much better exploited in the FRP products than in the massive glass and it is one of the promising materials for future constructions.

When does glass break? We have seen earlier that when tensile stress is applied on glass, it can accommodate the energy upto a certain limit by undergoing elastic deformation. When further stress is applied it cannot store the energy any more. To spend this energy it breaks and forms new surfaces. It is important to note that to generate a new surface some amount of energy has to be spent and therefore when glass breaks it releases the excessive stress energy and transforms it to surface energy. Some

amount of energy is also spent in the forms of heat and the sound that is heard when glass breaks. Coming back to the analogy of tearing a piece of cloth, when a cloth is stretched, the little cut made at the edge of the cloth spreads down at right angle to the direction of the applied tensile stress. Similarly, in a glass the crack starts from one of the surface flaws where the stress is maximum and starts spreading at right angle to the applied stress. However, when a window pane is hit hard with a piece of stone we do not just see one crack but a number of them, which fan out radially from the point at which it starts (Figure 4.6). This is because the impact stress in this case is so high that it cannot be got rid of by propagation of a single line of crack. To release the excess energy quickly the body tries to generate new surface at a faster rate and to do so several cracks are formed. Figure 4.6 shows a typical crack pattern in a window glass hit by a solid body. Here we also notice that across the radial cracks there are also arcs of concentric circles with the point of impact as the centre. This crack pattern is responsible for the formation of dagger shaped 'splinters' which fly out of the glass under a sufficiently strong impact. In fact, formation of the splinters is a peculiar characteristic of glass not to be found in other materials of construction.

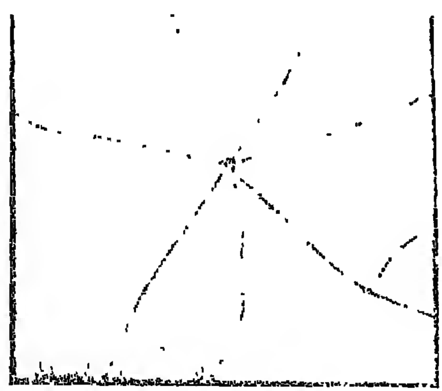


FIGURE 4.6 *Fracture pattern of a window pane*

Particularly interesting is the fracture pattern of toughened glass which is quite different from that of an ordinary glass. The photograph in Figure 4.7 vividly shows how cracks spread

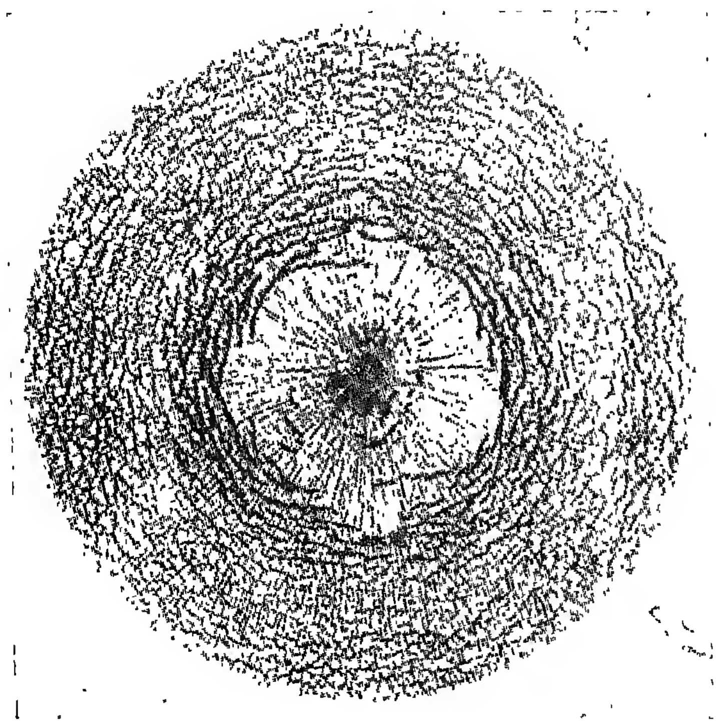


FIGURE 4.7 *Fracture pattern of a toughened glass plate*

through a glass plate toughened by quenching. The picture shows that numerous cracks are spreading radially from the starting point in the form of an almost perfect circle. Across the radial cracks there are circular cracks concentric to the centre. The

result is that the pieces of glass produced by shattering the toughened sample are much smaller in size and larger in number. Generally, the stronger the glass the smaller are the fractured pieces formed for reasons explained in the earlier para. In fact, it is possible to estimate the toughness of a glass by counting the number of pieces into which it breaks. For instance, a well toughened glass used in motor car windshields should crack into 10 to 15 pieces per square inch area. Another interesting feature of toughened glass is that even after cracking, the pieces do not easily fly off from a broken sample in the form of splinters; instead, they remain there as rounded grains and this makes their use safer.

Laminated glass: This is a glass-plastic composite in which a layer of plastic is sandwiched between two plates of glass. Although a laminated glass is slightly weaker than a single plate of glass having the same thickness, when it breaks under a sudden shock due to an impact or an explosion, the broken pieces stick to the plastic layer and thus the hazard of flying splinters is avoided.

The laminated safety glass is widely used for glazing almost all types of vehicles including motor cars, aircrafts and space vehicles. The common variety which is extensively used in some of the automobiles consists of two glass plates of about 0.3 cm thickness with a thin sheet of a plastic material (polyvinyl-butyrate) in between the glass plates.

Glazing of aircraft windows, however, poses several engineering problems. It is expected to withstand the impact of heavy birds and the heat and tremendous air pressure particularly when the aircraft is breaking the sound barrier. The laminated glass used for the purpose has therefore to be strengthened further. Thicker and toughened glass plates are generally used for lami-

nation instead of ordinary sheets of glass. The plastic layer is also much thicker and it extends beyond the glass layer. The extended layer is further reinforced with metal to improve the strength and resistance to complete failure. The inner surface of the outer glass plate is given a special coating of a transparent material which conducts electricity and this conducting layer is connected to an electrical power source. When current is passed through the layer it keeps the glass warm and thus prevents formation of ice on the outer surface.

The so-called bullet resisting glass is also a special type of laminated glass consisting of four layers of plate glass instead of two, and three sheets of plastic sandwiched between the layers of glass. When a bullet strikes the outer glass plate it will shatter to release a portion of the stress produced as a result of the impact. The remaining amount of stress will be transmitted to the adjoining plastic layer which has to be strong enough to absorb it and thus arrest the spreading of cracks to the inner layers of glass. Tests have shown that a 75 mm thick sandwiched glass of 6.25 cm^2 area will stop a hit from a 30 calibre armour piercing bullet. To stop a 50 calibre bullet a total thickness of 150 mm is required. In such thick glasses it is important to ensure that the visibility remains good. Sufficiently clear sheets of glass and plastics having the same refractive indices have therefore to be used for the purpose. The bullet proof glass is used in some of the military aircrafts, gun sights and sometimes in banks, jewellery stores, special motor cars, etc. It is also used as an observation window in test chambers operating at high pressure.

A new development in this field of laminated glass is a sandwiched composite consisting of as many as forty layers of thin paper-like sheets of glass with layers of plastic between them,

This multiple sandwich is reported to have much better shock resistance compared to the conventional type of laminated glass of the same thickness. Production of this item is, however, still in the experimental stage.

5

In the Service of Man

THE GLASS BARRIER

PHYSICAL energy is manifested in various forms such as heat, light, electricity, sound, etc. Whatever may be the form of energy its natural tendency is to flow down from a higher to a lower level. Water kept in a reservoir on a hill top would tend to flow down the valley and during this process would transfer mechanical energy to the turbines for generation of hydro-electric power. Similarly, the heat energy generated inside a locomotive boiler flows down to a lower temperature level giving up its excess energy for driving an engine. When electricity passes through a resistance the voltage (electrical pressure) drops and the electrical

energy lost by this process is transformed to heat and light. Therefore, in order to get useful work out of any form of energy it has to be kept at a higher level and allowed to flow down to a lower level through a suitable device—such as turbines, heat engines, filaments in incandescent lamps, motors, etc. During generation, transmission and actual use of energy it should not be allowed to leak out without performing useful work and for this purpose it is necessary to build adequate barriers which are in certain cases known as insulators.

Insulation against heat: When a room or a refrigerator chamber is to be cooled some amount of heat is 'pumped out' of the system by using a suitable device and as a result, the temperature drops. Similarly, heat has to be 'pumped in' to warm a room or heat up a baking oven. However, the natural tendency of the heat energy is to flow in or flow out as the case may be, in order to even out any difference in temperature. To prevent this undesirable leakage of heat energy, a suitable barrier has to be built around the space to be heated or cooled. The metals conduct heat very quickly and they are not therefore suitable for the purpose. Cement, building bricks and glass in its usual massive form are somewhat better but they leave more to be desired. For example, thermal conductivity of a block of copper metal is as much as 2900 BTU/hr./sq. ft./°F/inch. The corresponding value for building brick is about 4.0. Compared to this the thermal conductivity of glass wool is as low as 0.3.

We have already come across the use of glass in the form of fibres for insulation. Another form of glass which is used for insulating purposes is 'foam glass'. This queer material does not look like glass at all. Usually it is a dark coloured material having numerous pores entrapped inside the glass and as a result,

it is very light. In fact it floats in water (Figure 5.1). Thermal conductivity of foam glass is generally as low as 0.4 BTU/hr./

FIGURE 5.1 *Foam glass—a light weight material being used for insulating the roof against heat.*

sq.ft/°F/inch. The material therefore acts as an excellent insulator and bricks made out of foam glass are used for insulating air-conditioned rooms, refrigerators and cold storages, in which food materials are preserved. The insulating property of foam glass is due to the presence of numerous pores entrapped inside the material through which hardly any heat can flow.

Conduction of heat can take place only through a material body and therefore the ideal barrier against flow of heat is vacuum. This idea has been utilised in the construction of a thermosflask—a common article of glass in which we can keep things hot or cold for a long time. A thermos flask is essentially a double walled glass container (Figure 5.2) in which the space between the two walls is evacuated. This evacuated space acts as a highly efficient barrier preventing any flow of heat from outside or inside. A hot body also loses its energy by radiation particularly at higher temperatures. One way of reducing heat loss is by *reflecting* the heat rays back from a mirrored surface and this is what is done in a thermos flask to reduce radiation loss. As shown in Figure 5.2 the entire glass surface surrounding the evacuated space is given a silver coating which reflects back radiant heat and by this process heat loss is further minimised.

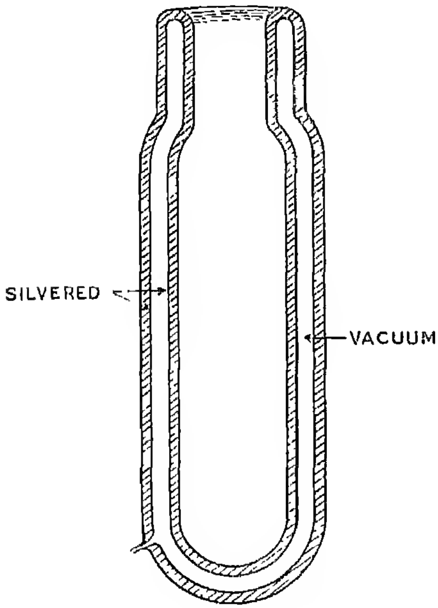


FIGURE 5.2 *Diagrammatic sketch of a thermos flask*

Insulation against sound: Sound is also a form of energy generally produced by vibration of a material body. In a busy city or an industrial area, a large variety of sounds of different intensities are constantly produced. In order to insulate a building against excessive external noise a suitable

barrier, which will reduce the noise level to a tolerable limit, has to be provided. The unit in which the intensity of sound is expressed is 'Phon'. The levels of loudness of some of the common sources of noise in a city are given in Table 5.1 in terms of phons.

Sound reaching a partition from an external source as airborne vibration can be transmitted inside by two different processes. (i) The external noise can get inside through any cracks in a partition or gaps around the edges and these have to be avoided in any efficient sound insulating device. (ii) The partition as a whole may vibrate and thus initiate sound waves inside the building. A brick wall is generally too heavy to transmit sound inside by vibration but the effect can be quite substantial in the case of glass panes which are much thinner and can be made to vibrate by an external sound more easily. The heavier the glass used in the window, the lower is the amount of noise transmitted through its vibration. The glasses generally used for the windows of buildings can reduce the noise by about 25 to 30 phons provided, of course, there is no air leakage in the window. A more efficient way of reducing the noise is to use double-walled glass windows in which two glass panes are mounted independently. By using heavier window panes and suitable mounting devices it has been possible to reduce the noise by as much as 55 phons or even more. This would mean reducing the sound from a noisy canteen (Table 5.1) to the level of a low whisper. Double-walled glass blocks such as those shown in Figure 1.11 also act as fairly efficient sound barriers reducing the noise level by some 40 phons or so. It may be mentioned here that by properly designing the glass blocks it has been possible not only to reduce the noise level but also to get a more uniform illumination in a room and cut off the excessive heat and glare of the midday sun in summer. In view

of these advantages hollow glass blocks are sometimes used in modern architecture.

A window glass acts as a reflector of sound. Generally 70 to as much as 99 per cent of the sound energy reaching a rigidly fixed glass surface is reflected back. In contrast, fibre glass products in the form of boards, mats, etc. are highly efficient absorbers of the sound energy. In a cinema or concert hall the sound waves are normally expected to reflect back from the wall surface particularly when marble or such other polished materials are used and produce undesirable echoes inside the hall. This is avoided by covering the wall with a soft sound-absorbing material such as fibre glass. Sound absorption is one of the important qualities of certain fibre glass products which leads to their use in construction of various structures including aircrafts and spacecrafts.

Electrical insulation: As mentioned earlier during the process of generation, transmission and use of electricity in various devices, it is important to ensure that the electrical energy does not leak down to the earth. Let us consider the electrical power lines that we see running across the fields, carrying electrical energy from generating stations to distant cities and industrial areas, at voltages sometimes as high as several hundred thousand volts. These long arteries of power are required to function properly under all weather conditions and the insulators used in such power lines must have adequate mechanical strength, resistance to weathering action and extremely high resistance to flow of electricity. Glass can satisfy these exacting demands.

Usual soda-lime-silica glasses hardly conduct any electricity. In other words, they behave as good insulators for most practical purposes and are widely used as electrical insulators in telegraph

and telephone lines through which current passes at comparatively low voltages. For insulating high tension lines, however, a better non-conductor is required. Generally, the insulating quality of glass improves when the alkali content (soda and potash) in the composition is low. Pyrex types of glasses which contain comparatively smaller amounts of alkalies are sometimes used as insulators in high tension power lines. Recently, other varieties of glass, such as those containing aluminium and magnesium oxides and very little alkalies, are also reported to be extensively used as insulators in high voltage power lines. Other important uses of glass as a high voltage insulating material are in the construction of x-ray generating tubes, special types of switches (mercury switches), power fuses in transformers, circuit breakers, etc.

Glass is also extensively used in the construction of various electronic components. In order to transform sound to radio signals in the broadcasting station and then to reconvert the radio signals to sound at the receiving station, electronic valves or transistors are used. Frequency of the radio signals encountered in radio valves and other electronic components is very high (of the order of 10^6 cycles per second) as compared to the frequency of only 50 cycles per second for ordinary AC power lines. An ordinary soda-glass which has fairly high resistance at 50 cycles will, however, show much lower resistance at radio frequencies and is not a suitable insulating material for high frequency circuits. Special types of glasses, (lead glass, borosilicate glass, etc.) having comparatively smaller amounts of soda are used in such cases. To an electronic engineer such glasses are known as 'low dielectric loss' glasses. The insulators used in radios, antennae, electronic tubes, etc. are of these types. Some of the other important glass components used in electronic devices

are television tubes, ribbon glass in electronic condensers and the 'sealing glasses' used for sealing metallic components into glass

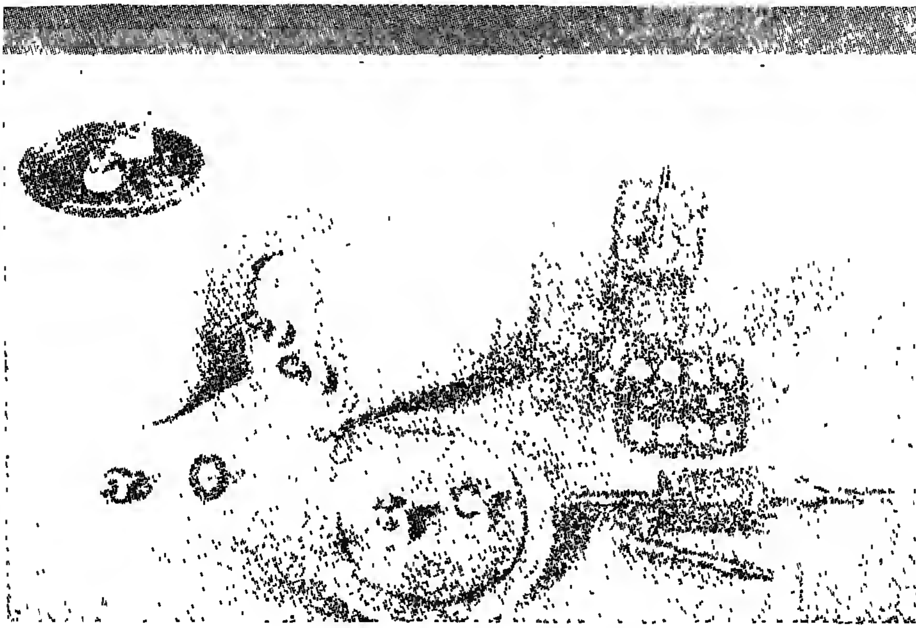


FIGURE 5.3 *Glass-to-metal seals used in electrical and electronic devices (a) Caps for compressors in refrigerators (b) Seals for silicon diodes (c) Transistor headers (d) Multiple pin seals for electronic relays.*

insulators. These seals are produced by heating a glass and a metal together till the glass softens and sticks firmly to the metal surface. Figure 5.3 shows some of the common glass-to-metal seals used in various electrical and electronic devices. They are used wherever metal electrodes are to be inserted inside a closed gas-tight space.

So far we have considered glass as an electric insulator for use in high voltage as well as high frequency circuits. Recently, a number of unusual glass compositions containing oxides of phosphorous, vanadium, tungsten, germanium, etc , have been developed which show relatively high electrical conductivity. A family of non-oxide glasses containing arsenic, antimony, sulphur, selenium, telluriam, etc., also shows unusual electrical behaviour. These 'semi-conducting' glasses, as they are called, are finding highly interesting and sophisticated applications in the field of electronics such as memory switches, integrated microcircuits, etc. It is also hoped that some of the oxide semi-conducting glasses may be used to develop more efficient lighting systems utilising the phenomenon of 'electro-luminesences'. Here, instead of thc glowing filaments, the entire area of electro-luminescent glass emits light when small amounts of electrical energy flow through the glass. This method of area lighting is more efficient and may largely replace the present incandescent lamps and fluorscent tubes.

GLASS IN THE ATOMIC AGE

Ever since the epoch-making explosion in Hiroshima in the year 1944, a large number of scientists and technicians all over the globe have been engaged in harnessing atomic energy. Indeed we live in the atomic age. Various types of nuclear reactions are now being utilised for liberation of atomic energy and production of radio-isotopes, which are used in medicine, agriculture, industry and scientific research During the course of such nuclear reactions certain radiations are produced which are known to have harmful effects on man and other living objects and one of the important problems in industrial plants or a research laboratory where radio-

active materials are handled is the protection of personnel from these dangerous radiations. Thick sheets of metallic lead or certain special solutions kept in a glass cell have been reported to be used as absorbing shields for protection against radiation. If these harmful radiations could be absorbed by a transparent glass then it would offer operational advantages. This had, therefore, stimulated a considerable amount of work for the development of glasses which can absorb atomic radiations.

In each atom there is a heavy positively charged nucleus around which negatively charged electrons move in different orbits. In a way, they are like planets moving round the sun. The nuclear mass mostly consists of the positively charged protons and neutrons, which have the same mass as that of a proton but no charge. In addition to these, there are also various other nuclear particles which we need not discuss here An atom of each element has a definite number of electrons and an equal number of protons in the nucleus to balance the charge. For instance, hydrogen has only one electron and one proton and is therefore the lightest of all the elements. On the other hand the element uranium has as many as 92 electrons and an equal number of protons in the nucleus. In addition to these protons there are also neutrons to bring the total to 238 or so. Uranium is, in fact, the heaviest of the elements present in nature. Weights of atomic nuclei of all the other elements lie between these two extremes.

When the number of protons in a nucleus exceeds a certain number, the nucleus becomes too heavy to remain stable and it breaks down spontaneously. Comparatively lighter elements, which are normally stable, can also be broken down by artificial means. When an atom breaks, various types of radiations come out from it. They can be broadly classified under two categories, viz.

charged radiations consisting of α-particles, electrons, etc. and uncharged radiations such as γ-rays and neutrons. The charged types are easily absorbed by matter and do not offer any special problem. The uncharged radiations are, however, highly penetrating and often elaborate arrangements have to be made for protection against them.

Like the x-rays, the γ-rays are electromagnetic radiations of very short wave lengths and when they impinge on a material body, different types of reactions are possible depending on their energy and the weight of the atoms present in the body. Absorption of

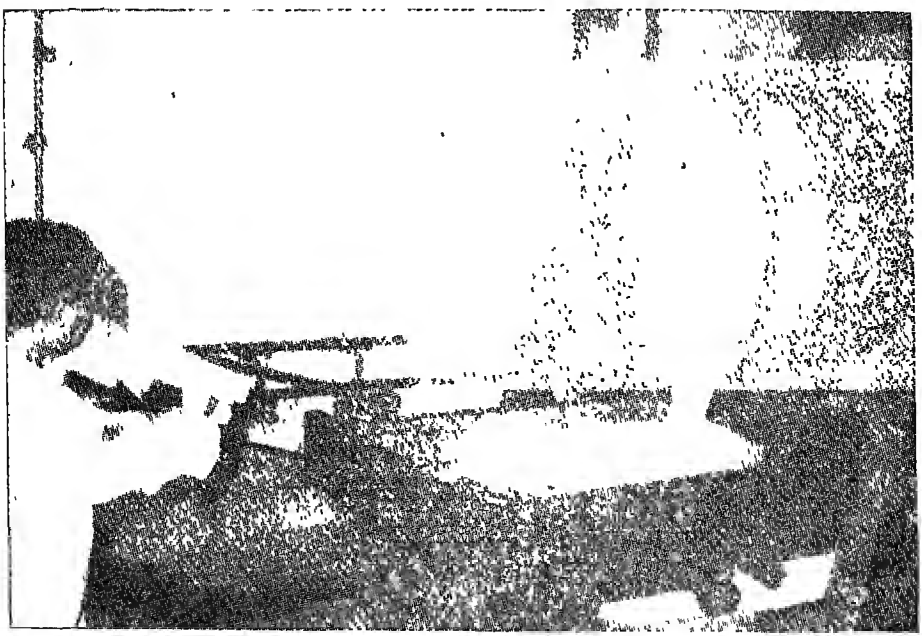


FIGURE 5.4 *Pouring of radiation shielding window glass into a forming mould.*

γ-rays by a piece of matter is more, the larger the weights of the atoms present in the medium. Ordinary glasses containing comparatively lighter atoms such as silicon, calcium, sodium, etc. (in addition to oxygen), have low absorption power. Special compositions had, therefore, to be developed for the purpose, so that the glass would contain a maximum amount of heavier elements and a minimum of oxygen which has a low absorbing capacity. High absorption efficiency is not, however, the only criterion; to be of any practical value, the glass should also be capable of being easily melted, cast in the form of transparent blocks (Figure 5.4) and should have sufficient resistance to weathering action. One of the snags in exposing ordinary glass to high energy radiations is its discolouration and consequent decrease in transparency. Certain ingredients such as cerium oxide (known as deactivators) have therefore to be added to retard this process.

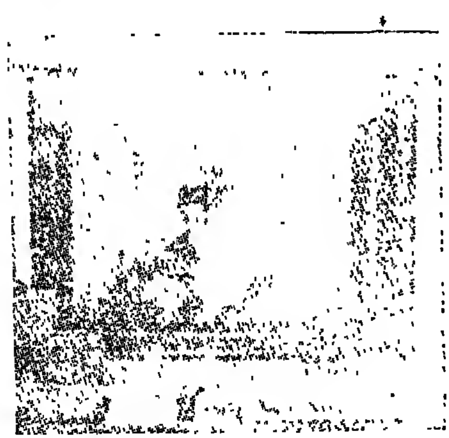


FIGURE 5.5 *A scientist watches handling of radio-active materials through a radiation absorbing glass.*

An unusual glass composition satisfying these requirements consists of lead oxide (60 percent), tungstic oxide (20 percent), phosphorous pentoxide (16 percent) and small amounts of titanium dioxide, etc. added as deactivators. A 1 cm thick block of this glass will absorb the same amount of γ-rays as a 0.6 cm thick sheet of metallic lead. There are also other types of compositions such

as those containing large proportions of barium oxide and lead oxide, which have sufficiently high absorbing power to be used for the purpose. Figure 5.5 shows a thick window of such a special γ-ray absorbing glass through which a scientist, at the Atomic Energy Establishment in Bombay, watches handling of highly radio-active materials. All the operations in the chamber are carried out with the help of two 'mechanical hands' which can be actuated from outside. Radiation shielding glass blocks have been produced at the Central Glass and Ceramic Research Institute in Calcutta.

Like the γ-rays, neutrons are also highly penetrating. Absorption of neutrons depends largely on their energy content which is measured in terms of electron volts, one electron volt being the kinetic energy of an electron falling through a potential of one volt. Fast neutrons having energies higher than one million electron volts are very highly penetrating. Absorption of fast neutrons is more, the heavier the atom. An x-ray or γ-ray absorbing glass should therefore absorb more of fast neutrons although the efficiency of absorption would be much smaller than that for γ-rays or x-rays. As regards the slow neutrons, two unusual elements, namely gadolinium and indium, have been found to have the highest absorbing power and it is possible to make clear glasses containing substantial amounts of oxides of these elements although the cost of such glasses would be prohibitive. Glasses containing boric oxide together with comparatively small amounts of indium, gadolinium, lanthanam and a few other oxides have fairly high absorbing power. Silica, which is by far the most important constituent of common varieties of glasses, can, however, hardly absorb any neutron; as a matter of fact, a silica glass can be used as a neutron transmitting glass.

We have seen that oxides of heavy elements such as lead, barium, tungsten, etc. are used in the x-ray or γ-ray absorbing glasses. For similar reasons, the lighter elements absorb very little of these radiations. The lightest element is hydrogen, and the next is helium. Both of them are, however, gaseous. The next ones Nos. 3, 4 and 5 are lithium, beryllium and boron respectively. Oxides of these elements can be melted together to form a special type of glass known as Lindemann Glass. Such glasses are almost completely transparent to X-rays and are used when high transmission of x-rays is necessary. The windows of the x-ray generating tubes through which the rays come out are sometimes made of this glass. These glasses are also used for carrying out various scientific studies with x-rays and γ-rays.

When atomic radiations pass through glass and other materials they bring about various changes in the constituent units with which the material is built up and the process is commonly known as the 'radiation damage'. When glass is exposed to such radiations it is discoloured as a result of these processes. Recently, some special types of glasses have been discovered in which the intensity of colour developed depends on the amount of radiation to which it is exposed. These glasses can be used to measure the dose of harmful radiations. For example, a person carrying a dosimeter glass while working with radio-active materials can find out if the dose of radiation to which he is exposed is harmful or not by noting the extent of discoloration of the glass.

Recently, it has been observed that when certain fast moving heavy nuclear particles impinge on glass they penetrate through the glass and damage the areas surrounding their path When the glass is afterwards treated with certain chemicals, the damaged areas are easily dissolved and they show up as tracks or pits when

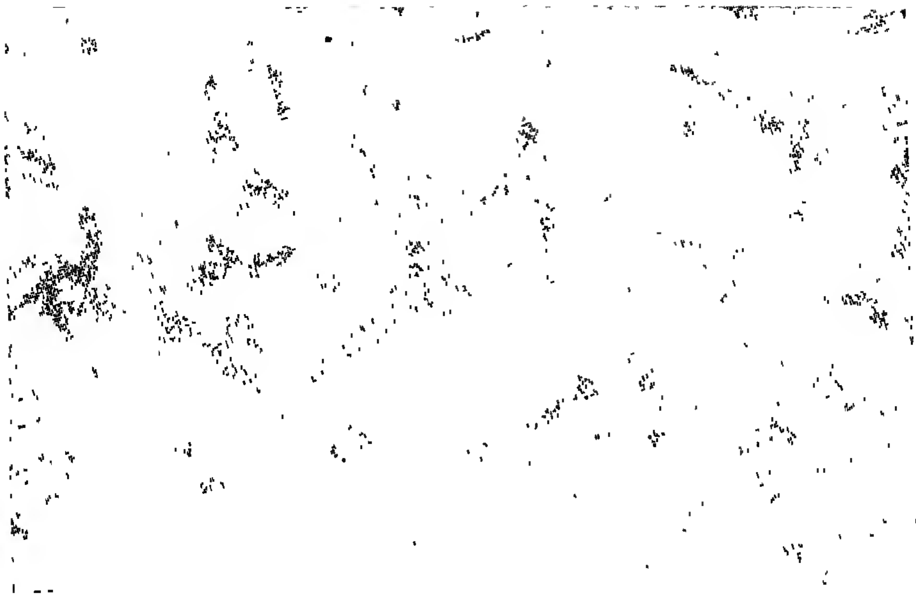


FIGURE 5 6 *Heavy ions damage in a track detecting glass. When developed chemically they appear as tracks along the ion path. Fission fragments of* U^{235} *produced by neutron activation are used as ions in this case which leave a track of about 20 microns in length. Magnification: about 1500X.*

seen under a microscope. Special types of glasses have been developed which can be used for detection of tracks due to the passage of heavy nuclei. Figure 5.6 shows such nuclear tracks in a glass developed at the Central Glass and Ceramic Research Institute. In this case the glass is exposed to fast moving neutrons which break the nuclei of uranium atoms present in the glass. Such a process is known as 'nuclear fission'. Fragments of broken uranium nuclei are relatively heavy nuclear particles and

the observed tracks are due to passage of these particles through glass. This type of track detecting glasses can be used to study a variety of nuclear phenomena because of the extreme simplicity of the technique, and it holds promise for future researches in the fields of atomic and space science.

Another area in which glass is finding important use is in disposal of radio-active wastes. The waste materials from nuclear 'reactors', producing electrical power, isotopes, etc , remain highly radio-active and they cannot be allowed to remain in open. Particularly harmful are the elements strontium, ruthenium and cesium, which remain dangerously reactive for several years. These elements can now be converted into oxides and dissolved in a molten glass having a special composition. The glass will retain the 'active' materials almost indefinitely and can safely be dumped underground or in deep seas without any danger of future contamination.

NEW HORIZONS

We have known that since time immemorial articles of glass are being produced by man as objects of beauty and common utility. Since the turn of the present century, there have been revolutionary changes in the age-old art of glass making as a result of which not only has the total production of glass recorded a phenomenal increase but also its width of application extended in the modern home and in various branches of science and industry. One of the important reasons for the rapid growth of glass industry and its promising future is that the materials used for making common glass namely soda, limestone and sand are cheap and almost inexhaustible.

The success of glass in modern life is primarily due to the

unique combinations of various useful properties that cannot be obtained in any other material. A common glass, for example, is hard, transparent and fairly resistant to chemical attack, heat and flow of electricity. These qualities account for the extensive use of glass in making containers, window panes, electrical insulators, etc and numerous other articles of common utility. There are also situations where completely different properties are required and today, as a result of intensive scientific researches, it has been possible to vary these properties of glass within a very wide range and even to 'tailor' a glass composition to the required properties.

Let us, for instance, consider the chemical durability of glass. As we have seen earlier, some glasses are strongly resistant to corrosion of water, acids and alkalies and this has been largely responsible for their extensive use in the manufacture and preservation of chemicals, medicinal preparations and food materials. Use of glass containers is increasing at such a fast rate that their disposal from urban areas is likely to pose a problem in future. To overcome this difficulty thought is being given to the possibility of making soluble glass containers, having only a thin chemically resistant coating at the surface. After their use they can be broken and easily disposed of in rivers or the sea. We have also come across the use of glass for disposal of dangerously radioactive waste materials, which is vitally important in modern nuclear technology. Another important use of glass is for direct chemical estimation of certain elements in a solution. For such purposes, special varieties of glasses have been developed which are allowed to react chemically with the solution, and as a result of this limited and controlled chemical reaction, an electrical voltage is developed at the interface of glass and the solution. By measurring this voltage it is possible to estimate the acidity or alkalinity

of the solution. These glasses are known as 'electrode glasses'. Various types of glass electrodes are now available for measuring the acidity and also elements like potassium, sodium, magnesium, calcium, etc. when they are present in a solution. (Fig. 5.7). Special electrode glasses are used for measurement of CO_2 in blood during surgical operations.

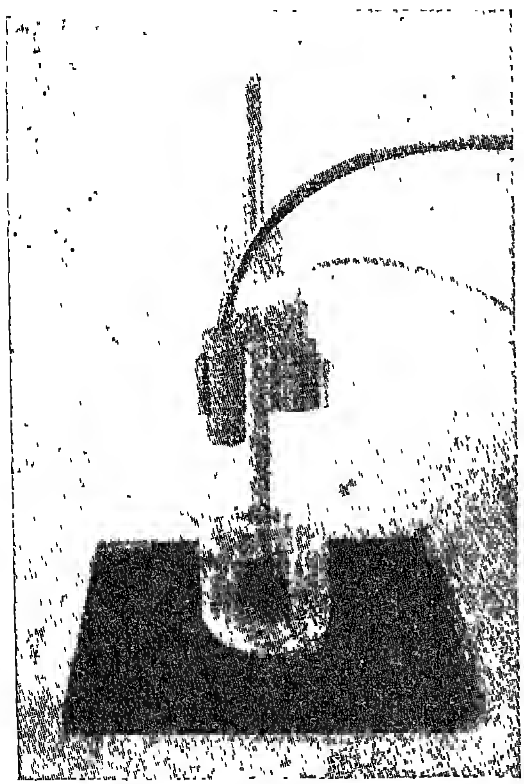


FIGURE 5.7 *Glass electrode, for chemical testing and analyses of solutions, produced at the Central Glass and Ceramic Research Institute.*

Perhaps the most important of all the properties of glass are the mechanical properties. Glass is commonly known to be delicate and fragile—but we have already come across special types of glasses having strengths around several thousand kilograms per square centimeter compared to only about 50,000 psi for mild steel. In fact, some of the fibre glass products have very high strength to weight ratio and glass fibre reinforced plastics have already replaced metals in many places as a structural material. For example, fibre glass structures are

already in use and promising attempts are being made to use glass fibres in the place of steel in reinforced cement concrete structures. Glass is also used as a lubricant for drawing steel at high temperatures.

Normally, glass behaves as a brittle material but recent researches have shown that after special treatment with certain chemicals it can be bent and twisted considerably without breaking. There are also chemically-machined, intricate glass shapes. By this novel process, it has been possible to make as many as 8,000 tiny holes per square cm. area of glass. New uses of these unusual products and processes may be found in future industries and scientific research.

As we have seen earlier an important characteristic of glass is its ability to transmit and absorb different portions of radiant energy. We have already come across various types of glass absorbing or transmitting x-rays, γ-rays, ultraviolet radiations, visible light and heat radiations. One of the interesting discoveries made in recent years is the 'Photochromic glass'. These contain certain special compounds such as silver bromide, which normally do not produce significant coloration. On exposure to sun rays these compounds break down to constituent elements, silver and bromine. Bromine is dark in colour and formation of free bromine leads to darkening of glass. The interesting feature of this glass is that when it is removed from the strong sunlight, the silver and bromine again recombine and as a result the glass becomes colourless. The reaction is therefore reversible. The stronger the light the greater is the decomposition and vice versa. The colour of glass becomes stronger or lighter depending on how strong is the light to which the glass is exposed. A window pane or sun goggles made of this glass would transmit more or less the same amount of

light whatever may be the intensity of the light rays falling on it. This is, therefore, an ideal material to achieve a more or less uniform level of indoor illumination throughout the day. This glass has proved to be quite popular for use in spectacles and would automatically become dark or light depending on the level of illumination.

Another important development in the field of optics has been the 'Fibre optics'. Here, instead of lenses and prisms the optical element is a thin fibre of glass. Although it sounds fantastic, the basic principle is fairly straightforward. Let us take an optical glass rod, coated with a layer of another glass having a lower refractive index. If we shine a beam of light at one end of the rod most of the light comes out through the other end. If the rod is twisted in the form of a spiral, still the light will travel all along the spiralled path by internal reflections and come out through the other end. The same thing would also happen in a fibre of glass, which is, in fact only a very thin rod of glass. By shining light on one end of a glass fibre it is possible to illuminate the area facing the other end and this simple observation has led to several interesting developments; it has been possible, for instance, to illuminate internal human organs for medical observations or surgical operations by inserting thin glass fibres inside the body and shining light on the external end of the fibre. Researches are still in progress on various aspects of fibre optics and on practical applications of this novel technique.

Yet another interesting glass product developed is the 'Laser glass'. A laser is essentially a source of an extremely intense beam of parallel light. The light produced is so very bright that it can even be made to hit the moon and bounce back to earth. Although gases and certain crystals such as sapphire are commonly

used for generation of optical laser beams, special types of glasses have also been developed for the purpose. These are optically perfect glasses containing certain rare elements such as neodymium. One of the many possible applications of the light beam generated by laser glass is its use as carrier waves (instead of the conventional radio waves) for long distance communication through an optic fibre.

The story of glass would not be complete without a word on lunar glass. At the beginning of this book we came across the natural glass, Obsidian (Figure 1.1), formed by rapid cooling of the volcanic mass. We can reasonably expect that similar processes can also take place on some other planets and the moon. In fact, the sample of rocks and dust recently brought from the moon showed that some of them are glassy in nature (Fig 5.8). Closer examination of lunar glass revealed that the density of glass was not uniform. It varied probably because they cooled from the molten state at different rates, depending on the environmental conditions. The faster the cooling the lower is the density. It is hoped that studies on variations in the density of lunar glass will throw more light on the formation and thermal history of the moon.

It has been a long way from the discovery of glass on the banks of the river Belus to its use in spacecrafts and laser communication. These phenomenal achievements have not been made by strokes of luck but are the result of persistent efforts of scientists and engineers over a long period of time. And yet many more discoveries are still awaited. In the field of technology, for example, much is left to be desired by way of improving the efficiency of the glass melting process. As we have noted earlier as much as eighty per cent or even more of the heat energy that is put in for melting

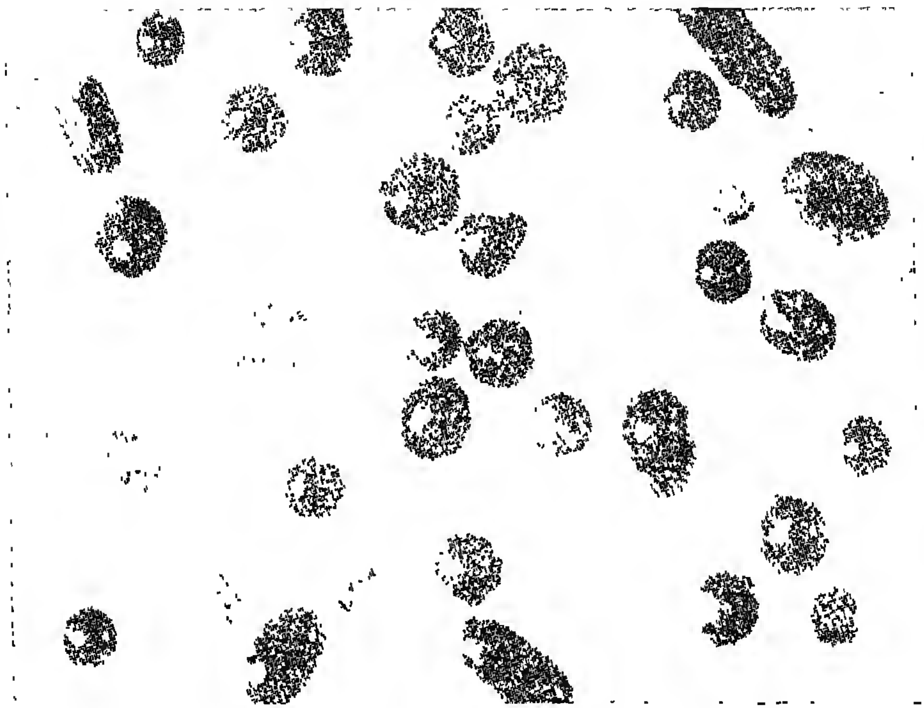


FIGURE 5.8 *The lunar soil contains a wide variety of glass beads. The average size of these particles is 0.2 mm. The beads are formed when the soil particles melt under impact of interplanetary dust particles and cool in the high vacuum on the moon.*

glass is still being wasted. There is also room for further improvements in the methods of forming glass so that better and cheaper articles can be produced at still faster rates.

Our understanding of the glassy state of matter is also far from being complete. We do not exactly know why certain

materials can be cooled from the liquid to glassy state without forming any crystals. Neither do we exactly know how the constituent units are arranged in a glass nor do we understand many of the fundamental properties of the glassy state of matter. Researches are in progress in these and many other fields to reach newer horizons of knowledge for the benefit of man.

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APPENDIX I

TABLE 2.1

TYPICAL CHEMICAL COMPOSITIONS OF SOME COMMON VARIETIES OF GLASS
(In per cent by weight of glass)

Major Constituents	*Container Glass*	*Window Glass*	*Laboratory Glass (Pyrex Type)*	*Incandescent Lamp Shell*	*Thermometer*	*Optical Glass (Flint)*	*Optical Glass (Crown)*	*Fibre Glass E-Type*
Silica (SiO_2)	73	72	81.5	73.5	74	32.5	70.0	54.0
Alumina (Al_2O_3)	1.5	1 0	2	0.5	6	—	—	13 0
Boric Oxide (B_2O_3)	—	—	12.0	—	10	4 0	11.0	10.0
Calcium Oxide (CaO)	9	10	—	6 0	0.5	—	—	18.0
Magnesium Oxide (MgO)	1	3.0	—	3 5	9 5	—	—	4.0
Sodium Oxide (Na_2O)	15	14	4 5	16	—	2.5	16.2	0.5
Potassium Oxide (K_2O)	0.5	—	—	0 5	—	—	—	0.5
Lead Oxide (PbO)	—	—	—	—	—	15.5	—	—
Zinc Oxide (ZnO)	—	—	—	—	—	8.5	—	—
Barium Oxide (BaO)	—	—	—	—	—	37.0	2 8	—

TYPICAL C

Constituents
Silica (SiO_2)
Alumina (Al_2O_3)
Boric Oxide (B_2O_3)
Alkaline earth oxide (RO)
Lead Oxide (PbO)
Lithium Oxide (Li_2O)
Sodium Oxide (Na_2O)
Potassium Oxide (K_2O)
Titania (TiO_2)
Other constituents

TABLE 3.1A

ANNUAL PRODUCTION OF DIFFERENT TYPES OF GLASS AND GLASSWARE*

	1961	*1966*	*1971*	*1975*	*1976*
Glass bottles, phials, etc (Thousand tonnes)	115	116 7	145		
Sheet glass (Million sq metres)	7.30	11.9	16.5	13.5	18.1
Shells for lamps (Million pieces)	62.8	90 3	137	154.3	162.5
Scientific glassware (Thousand tonnes)	3 6	5.4	0.9	2 5	2.2
Vacuum flasks (Million pcs)	2 7(1962)	—	3.8	5.1	4.9
Total glass production (Thousand tonnes)	225	291	290	300	330

**Figures from 1971 onwards exclude production by small scale industries.*

TABLE 3.1B

EXPORT/IMPORT OF GLASS AND GLASSWARE

Rs. in lakhs

Year	*Export*	*Import*
1961—62	25	132
1966—67	44	108 4
1971—72	216	209.8
1974—75	589.1	341
1975—76	800	—
1976—77	900 estimated	—

TABLE 4.1

MECHANICAL STRENGTH OF VARIOUS TYPES OF GLASS AND CERTAIN OTHER COMMON MATERIAL

Type of Material	*Approximate Tensile Strength kg/cm^2*
Rolled plate glass	350
Polished plate glass	450
Sheet glass	600
Toughened glass	1,400
Glass fibre reinforced plastics	1,400—10,500
Polyester plastic	850
Aluminium	5,600
Steel	16,800
Glass filament	24,500

TABLE 51

Loudness of Some Common Noises

Outside	*Approximate Loudness (Phons)*	*Indoor*
Large turbo-jet air liner during take off; overhead at 40 metres	140	
Large piston engined air liner during take off; overhead at 40 metres	130	(Threshold of pain)
	120	
Electric train over steel bridge at 7 metres	110	
	100	Weaving shed
Two pneumatic road drills and compressor in open at 40 metres	90	Very loud radio at home
	80	Noisy canteen
	70	
	60	Moderate restaurant clatter
	50	Quiet radio at home
Quiet street in evening	40	
Quiet garden	30	
	20	Quiet whisper at 2 meters
	10	Threshold of
	0	audibility

Abstracted from "Glass in Architecture and Decoration" by R.M. Grath and A.C. Frost (The Architectural Press, London), pp 486-87,

APPENDIX II

Glass in the Service of Man

The following are some of the numerous types of glass products used in different industries and for scientific research :

I. Atomic Energy

1. x-ray and γ-ray absorbing shield.
2. x-ray and γ-ray transmitting window in scientific instruments (Lindemann glass).
3. Glass for fixation of radio-active waste.
4. Dosimeter for measuring amount of exposure to nuclear radiations.
5. Detection of nuclear tracks and study of nuclear reactions.

II. Chemical

1. Containers, such as, ampoules, phials, bottles, jars, tanks.
2. Glass-lined metallic containers for processing of chemicals.
3. Pipings, tubings and centrifugal pumps for transport of chemicals.
4. Pipes for heat exchangers in chemical plants.
5. Cylinders for fractionating columns.
6. Guage glass in boilers and other vessels for observing liquid level.
7. Laboratory glassware for chemical research and testing.
8. Electrode glass for measuring acidity of chemicals and their analyses.
9. Electrode glass to monitor CO_2 concentration in blood during surgery
10. Sintered glass for filtration of liquid.
11. Glass wool for filtration of air.

III. Electrical

1. Insulators and lightening arresters in power line.
2. Envelopes and other components in electronic valves.
3. Special glasses for sealing with metals in electrical equipment such as transistor headers, diodes, relays, sealed compressor units in

airconditioners, oil filled capacitors, etc.
4. Components in electric condensers (glass ribbons).
5. Insulator for Radio antennae (low dielectric loss glass) and in high frequency circuits.
6. x-ray generating tubes.
7. Glass plates with printed circuits for radio receiving sets, etc.
8. Rocket and aircraft nose-cones.
9. Electrically conducting glass in micro-circuits.

IV. **Lighting**

1. Envelopes and other components in incandescent lamps.
2 Tubings for mercury and sodium vapour lamps.
3. Tubings for fluorescent lamps and neon signs.
4. Envelopes and heat-absorbing lenses for projection lamps.
5. Photoflash bulbs.
6. Ultra-violet transmitting glass for photographic filters, germicidal lamps and other sources of ultra-violet light.
7. Infra-red (heat) transmitting glass for 'Black light vision filters', long wave infra-red transmitting glasses (e g. arsenic sulphide glass) for communication, night photography, medical diagnosis, etc.
8. Phototropic glass for controlled illumination. (The glass automatically darkens with increasing intensity of daylight and vice versa).
9. Photo-sensitive glass for reproduction of pictures in glass.

V. **Optical**

1. Lenses, prisms and mirrors for construction of optical instruments such as microscope, telescope, spectograph, etc.
2 Eye protecting glasses such as welders' glass, sun goggles, etc.
3. Ophthalmic glass (spectacle glass).
4. Coloured signal glass (for traffic control).
5. Laser glass for generating Laser beams.
6 Optic fibres for examination of internal organs (Endoscopes) and for image intensifiers.
7. Optic fibres for communication systems such as telephones.

VI. **Mechanical**

1. Jewel bearings for precision instruments.
2. Optically flat surface plates.
3. Tortian fibres in instruments.
4. Accurate bore tubings for flow metres.
5. Moulds for fabrication of rubber and plastics.
6. Diffusion vacuum pumps.
7. Rollers and thread guides for the textile industry.
8. Fibre glass filters for air and liquids.
9. Fibre glass yarns and textiles.
10. Chemically machined intricate glass shapes; computer punch cards.
11. Glass lubricant for drawing metal.

VII. **Structural**

1. Window glass, plate glass and mirrors.
2. Building blocks and double-walled window glass for insulation against heat and sound, and for controlled internal illumination
3. Laminated safety glass and/or toughened glass for wind-shields in automobiles, aircrafts, space craft, etc
4. Fibre glass for absorption of sound and vibrations.
5. Fibre reinforced plastics, a versatile light-weight structural material for construction of buildings, automobiles, boats, aircrafts, chemical plants and equipment, and numerous implements of common use.

VIII. **Thermal**

1. Heat-absorbing flat glass for windows.
2. Thermos flasks.
3. Thermometers.
4. Glass hollow spheres of a few microns dia for low temperature insulation, used in the field of cryogenics.

APPENDIX III

Glossary of Terms Relating to Glass and Glass-Making

(From the Indian Standard Specification IS: 1382-1961)

Alabaster Glass — A milky-white glass which diffuses light without fiery colour resembling the mineral alabaster.

Alkali — (a) Carbonates of sodium (Na_2CO_3), potassium (K_2CO_3) and less frequently lithium (Li_2CO_3), used in describing the glass batch.
(b) Oxides of sodium (Na_2O), potassium (K_2O) and less frequently lithium (Li_2O), used in describing the composition of glass.

Alkalinity — A measure of the alkali extracted from the glass under specified conditions.

Amber Glass — Glass varying in colour between light yellowish-brown and deep reddish-brown.

Annealing — A process to prevent or remove objectionable stress in glass by controlled heating at and/or cooling from a suitable temperature.

Arsenic — Arsenic trioxide (As_2O_3).

Aventurine — Glass containing coloured, bright specks of metallic or other non-glassy material.

Baffle Wall — A wall, with or without openings through it, erected on the bridge cover to screen the working end from excessive heat radiation, also called 'Curtain Wall' or 'Shadow Wall'. It may also be a suspended wall above the bridge. (See Figure 2.2)

Barium Crown Glass — A crown optical glass containing significant quantities of barium oxide.

Barium Flint Glass — A flint optical glass containing significant quantities of barium oxide.

Batch — The raw materials, properly proportioned and mixed, for delivery to the furnace.

Batch House — A place where batch is prepared, also called 'Mixing Room'.

Bench Worker — A worker who forms glassware from tubing or rod by heating in a gas flame at a work bench, also called 'Table Blower'

'Blow Pipe Worker', 'Lamp Worker' and 'Glass Blower'. (See Figure 2 14).

Bicheroux Process — An intermittent process of making plate glass in which the glass is cast between rollers on to driven conveyor roller or a flat moving table.

Blank — (a) A preliminary shape from which a glass article is to be formed, also called 'Parison', (b) See 'Blank Mould' and (c) Any article of glass on which subsequent processing is required. (See for example Fig 2.7).

Blank Mould — The metal mould which first shapes the glass in the manufacture of hollow-ware, also called 'Parison Mould'. (See Fig 2.7).

Blisters — Relatively large bubbles or gaseous inclusions of more than 2 mm in minimum diameter in any direction.

Blooming — (a) Application to optical glass lenses of a non-reflecting film to reduce light scattering and back reflection.
(b) Process of deposition of chemical vapours.

Blow-and-Blow Process — A process of forming hollow-ware in which both the preliminary and final shapes are formed by air pressure.

Blow Mould — The metal mould in which a blown glass article is finally shaped.

Blown Glassware — Glassware formed by air pressure produced by mouth or by a machine.

Blow Pipe — (a) The iron pipe used by a glass-maker for gathering and blowing by mouth, also called 'Blowing Iron'.
(b) The burner used for working glass at a bench

Borate Glass — A glass in which boric oxide (B_2O_3) is the main glass former.

Borax Glass — Vitreous anhydrous sodium tetraborate ($Na_2B_4O_7$).

Borosilicate Crown Glass — A crown glass containing significant quantities of boric oxide (B_2O_3).

Borosilicate Glass — Silicate glass containing boric oxide (B_2O_3) as a characteristic constituent, usually above 5 per cent Borosilicate glasses are generally heat resisting.

Bridge Wall — Furnace wall separating the melting and working ends of a tank furnace.

Bubbles — Gaseous inclusions of 0.5 to 2 mm in minimum diameter in any direction.

Bursting Pressure — Glass of more than one layer of different colours, the top layer being carved in relief.

Cane — Solid glass rods of small or medium diameter.

Carboy — Large narrow necked glass container, usually of balloon shape, but sometimes more of a cylindrical shape having a capacity of more than 20 litres.

Cased Glass — Glassware having a surface layer of a compatible glass of different chemical composition, usually coloured.

Casting — A process of shaping glass by pouring it into a mould or on to a table or passing it between rollers.

Channel — That part of a feeder which carries the glass from the tank to the flow spout and in which temperature adjustments are made

Checkers — (a) The refractory bricks, alternating with openings, in the chambers of a regenerative furnace.

(b) The regenerators built in such a fashion.

(c) The refractory pieces used in such a fashion

Chemical Durability — The resistance of glass to chemical attack.

Chemical Glass — A chemically durable glass suitable for use in making laboratory apparatus or glassware.

Chipped Glass — A glass article with chipped surface produced intentionally.

Chunk Glass — Lumps of optical glass obtained in breaking open a pot of glass (Fig. 2A).

Clear Glass — Transparent glass.

Closed Pot — A pot made with a roof to protect the contents from flames and combustion gases in the furnace and with a mouth for removal of molten glass, also called 'Covered Pot' or 'Hooded Pot'.

Colburn Sheet Process — A method of making sheet glass by bending the vertically drawn sheet over a driven roller which determines the rate (definition) of draw.

Colouring Agent — Batch constituent used to give colour to the glass produced.

Colourless Glass — A glass which absorbs a negligibly small amount of visible radiation.

Container — General term applied to glass bottles and jars.

Continuous Tank — A glass furnace which is fed with batch at one end, whilst the molten glass is continuously withdrawn at the other. It usually consists of more than one compartment.

Cords — Glassy inclusion of different composition particularly in the form of drawn out lines and possessing optical and other properties differing from those of the surrounding glass.

Crackled — Glassware, the surface of which has been intentionally cracked by water immersion and partially healed by reheating before final shaping.

Crooke's Glass — A spectacle glass having low transmission for ultra-violet light, and containing cerium, and other rare earths

Cross-Fired Furnace — A glass tank furnace with pairs of ports along its melting end, so that flames travel across the furnace at right angles to the direction of glass flow. (See also 'Side-Fired Furnace').

Crown — The part of a furnace forming the roof, also called 'Arch' or 'Main Arch' in the case of a pot furnace.

Crown Glass — (a) A transparent glass made in disc form by blowing and spinning Crown glass has a natural fire-finished surface but it is of varying thickness with a slight convexity and so gives marked degree of distortion of vision and reflection.

(b) A type of optical glass not containing lead among its constituents and having low dispersion and usually low in refractive index.

Cullet — Broken glass added to the batch for remelting Factory cullet is obtained from within the works, foreign cullet from an outside source.

Cut Glass — Glassware decorated by grinding figures or patterns on its surface with an abrasive wheel followed by polishing; also called 'Deep cut'.

Cutting — (a) Making a cut of flat glass with a diamond or steel wheel so that it may be broken along the cut.

(b) Producing cut glass.

Cylinder Process — A method of making sheet glass in which a blob of molten glass is blown into the form of a cylinder which is subsequently split longitudinally. The split cyclinder is then reheated in a flattening kiln where it softens and becomes flat.

Decolourizer — A substance or mixture of substance added to the batch which counteracts the colouring effect of impurities. Its action is either physical (by imparting the colour complementary to that of the impurity), or chemical (for example by oxidation).

Decorating — (a) The firing of enamels on glassware.
(b) Applying designs to formed glassware by means of etching, sand-blasting, cutting, engraving or similar methods.

Devitrification — Development of crystals in glass

Distortion — An optical effect due to variation of thickness of sheet glass

Down-Draw Process — A process of continuously drawing glass tubing downwards from an orifice.

Drawn Glass — Glass, usually in sheet form, made by a continuous mechanical drawing operation

Embossing — Marking or decorating glassware by raised lettering or devices formed in the mould by blowing or pressing. (See also 'acid embossing').

Enamel Back — A glass tubing or rod in which an interlayer of opal glass is fused in

Engraved — Glass upon which a pattern has been incised with abrasive wheels.

Etching — Treating the surface of glass with hydro-fluoric acid or some other chemical, generally for marking or decoration, also called 'Acid Etching'.

Fade — Decrease in transparency or reflectivity, or colour intensity of glass.

Feeder — A device for delivering gobs of glass to a forming machine.

Fibre — An individual filament of glass less than 20 cm in diameter. A continuous filament is a glass fibre of great or indefinite length A staple fibre is a fibre of relatively short length (generally less than 40 cm.). A fibre of textile grade is one whose diameter is less than 8 cm.

Figured Glass — Flat glass having a pattern on one or both surfaces.

Figured Rolled Glass — A translucent rolled glass having a pattern on one or both surfaces.

Fine — A projection of glass caused by the entry of glass into a seam between mould parts during forming.

Fine Annealing — Annealing to an extremely low stress and uniform index of refraction.

Fire Finish — To make glass surface smooth and glassy by heating usually in a flame, also called 'Fire Polish'.

Flashing — (a) Applying a thin layer of glass to the surface of a glass of different colour in the forming stage.
(b) See 'Striking'.

Flat Drawn Process — A process in which a sheet of glass is drawn from a bath of molten glass and is passed between coolers to control thickness.

Flat Glass — A general term covering sheet glass and various forms of rolled glass such as plate glass, figured glass and wired glass.

Flint Glass — (a) A glass containing substantial proportion of lead
(b) A general term used for colouring glass of higher brilliance.

Float Glass — A form of flat glass produced by reheating the continuous ribbon of glass whilst it floats over a bath of molten metal.

Flux — A substance added to the batch to promote fusion

Foam Glass — A light weight multi-cellular glass having a homogeneous mass of sealed cells.

Forehearth — An extension of the working end of a tank furnace from which glass is taken for forming.

Forming — The shaping of hot glass.

Fourcault Process — The method of making sheet glass by drawing glass vertically upward from a tank through a slotted debiteuse block.

Frit — Calcined or partly fused materials which are subsequently melted to glassy state

Fusion — (a) Joining by heating
(b) Remelting for bead making.
(c) See 'Melting'.

Gather — (a) The mass of glass picked up on the blowing iron or punty.
(b) To collect glass from a pot or tank at the end of blowing iron or punty.

Glass — (a) An inorganic product of fusion which has cooled to a rigid condition without crystallizing
(b) A term frequently used to describe a tumbler.

Glass Blowing — The shaping of hot glass by air pressure applied internally.

Glass-Wool — Fleecy mass of plain glass fibres, also called 'Wool'.

Gob — (a) A lump of hot glass delivered by a feeder,

(b) A lump of hot glass gathered on a punty or pipe.

Ground Glass — Glass roughened by grinding with abrasive materials.

Hard Glass — (a) Commonly refers to a glass difficult to melt or fuse.
(b) A glass of relatively high viscosity at elevated temperature.
(c) A glass of high softening point and low co-efficient of expansion.
(d) Erroneously used also to describe glass of high chemical resistance.

Heat Resistant Glass — A glass having relatively high resistance to breakage due to sudden change in temperature, also called 'Flame Proof Glass' or 'Heat Proof Glass'. Heat resistance is usually accompanied by a low co-efficient of thermal expansion.

Ice Proof — A term used to describe containers (primarily tumblers) able to withstand sudden temperature gradients from the room temperature to that of ice

Intaglio — A form of decoration in which the depth of cutting is intermediate between deep cutting and engraving

Laminated Glass — A transparent sheet formed from interleaved, firmly adherent layers of glass and plastics material, the latter known as inter-layer or interleaf, having glass layers outermost.

Lampblown — Glass articles made usually from tubing or rod with the aid of a gas flame.

Lead Glass — Glass containing a substantial proportion of lead oxide (PbO) (Usually more than 15%)

Lehr — An oven, usually long and tunnel-shaped, for annealing glass, commonly by continuous passage through the oven.

Lens Fronted Tubing — Thermometer tubing formed so that the apparent width of the column of mercury or spirit is magnified.

Lime — Commercial calcium oxide (CaO); or a mixture of calcium oxide and magnesium oxide (CaO + MgO).

Limestone — Mineral calcium carbonate, or dolomite ($CaCO_3.MgCO_3$).

Liquidus Temperature — Maximum temperature at which equilibrium exists between molten glass and its primary crystalline phase.

Mandrel — Refractory tube used in the manufacture of glass tubing or rod

Manganese — (a) Commercial manganese dioxide (MnO_2).
(b) An industrial name for pyrolusite.

Melting — The thermal process by which the charge is completely converted

to molten glass, also called 'Fusion'

Melting Temperature — The range of furnace temperatures within which melting takes place at an economically desirable rate, and at which the resulting glass generally has a viscosity of $10^{1.5}$ to $10^{2.5}$ poises. For purposes of comparing melting temperature of glasses, it is assumed that the glass at its melting temperature has a viscosity of 10^2 poises.

Millefiori — A form of decoration used, for example, in paperweights, in which sections of multi-coloured glass canes are set in a clear glass matrix to form a design.

Moonstone Glass — Translucent glass resembling the mineral moonstone.

Mould — A form (usually metal) in which glass is shaped.

Mouthblowing — Shaping hot glass by air pressure applied with the mouth.

Neutral Glass — A glass of high chemical durability.

Nu value — The reciprocal, multiplied by one hundred of the dispersive power of an optical glass.

Obsidian — A black glassy natural rock containing a large propoition of silicates.

Opal Glass — Glass which is opalescent or white and made by the addition of fluorides (for example, fluorspar and cryolite), phosphates, arsenic compounds or tin compounds to the glass mixture; sometimes used to diffuse light.

Ophthalmic Glass — Glass used in spectacles usually having specified optical and physical properties and quality.

Optical Glass — A glass of special quality expressly made for its optical qualities from pure selected material under controlled conditions and so treated that the finished product is homogeneous and as transparent as possible for the whole visible spectrum and its contiguous spectral regions

Oven Glass — (a) Glass suitable for manufacture of articles to be used in baking and roasting goods.

(b) Glassware made from oven glass.

Oxidizing Agent — A mineral or chemical compound which raises the state of oxidation of other glass components during melting and thus helping in refining or controlling the colour of the glass.

Pilkington Process — A process for making flat glass in which the glass

continuously pours from a tank on to a spent and thence between forming rollers and is subsequently annealed as a continuous sheet.

Pittsburghs Sheet Process — The method of making sheet glass by drawing vertically upward from a free bath surface wherein the definition of draw is determined by a submerged refractory number.

Port — Any opening in a surface through which air, fuel or flame enters or exhaust gases escape; also called 'Burner'.

Pot — A round or oval refractory container in which glass is melted

Pot Furnace — A furnace for melting glass in pots.

Press and Blow Process — A process of glass manufacture in which the finish and parison are pressed and the parison is subsequently blown to form the final shape.

Pressed Glass — Glassware formed by pressure between a mould and a plunger.

Quartz Glass — A term applied to fused silica glass, when transparent; also called 'Fused Silica'.

Reducing Agent — A chemical which, at high temperature, lowers the state of oxidation of other batch materials

Refining — The state in the melting process of glass at which the undissolved gases are removed from molten glass, also called 'Fining' or 'Plaining'.

Regenerator — A cyclic heat exchanger which alternatively receives heat from gaseous combustion products and transfers heat to air or gas before combustion.

Ribbon Process — A process whereby molten glass is delivered to a forming unit in a ribbon form.

Safety Glass — A glass which, if fractured, produces fragments which are less likely to cause severe cuts than those of ordinary glass.

Saltpetre — Commercial potassium nitrate (KNO_3).

Sand — A source of silica for the glass batch, also called 'Glass Making Sand'.

Sand Blasting — Producing a matt surface on glass by projecting on to the surface a jet of small abrasive particles at high velocity

Seed — An extremely small gaseous inclusion in glass not more than 0.5 mm in any direction.

Sheet Glass — Flat glass made by blowing or drawing.

Signal Glass — Glasses in the shape of roundels or lenses used for signalling purposes, for example in the railways, aviation, etc.
Silica Glass — Vitreous silicon dioxide (SiO_2), pure silicon dioxide (SiO_2) glass.
Silvering — The application by chemical methods of a film of silver to a glass surface
Sintered Glass — Porous glass made for filtration or other purposes by heating graded glass powder.
Slab Glass — Optical glass obtained by quitting or forming the chunk glass into plates or slabs.
Soda — (a) Sodium oxide (Na_2O).
(b) Commercial anhydrous sodium carbonate (Na_2CO_3).
Soda-Lime Glass — Glass in which the main constituents are silica, lime and soda; also called 'Lime-Soda Glass'.
Soft Glass — (a) Glass with relatively low softening point.
(b) Glass having a low resistance to weathering.
Solarization — Change in transmission of glass as a result of exposure to sunlight or other radiation in or near visible spectrum.
Soluble Glass — Silicate of soda or potash, also called 'Water-glass'.
Stained Glass — (a) Glass coloured by fusing pigments to the surface.
(b) Windows made of pieces of stained glass or of coloured sheet.
Stemware — General description of stemmed glass drinking vessels.
Stone — Imperfections in glass resulting from inclusions from such sources as batch materials, refractories and blow pipes or resulting from devitrification of glass.
Strain — Elastic deformation due to stress.
Strength — Tensile strength of glass.
Stress — Any condition of tension or compression existing within the glass, particularly due to incomplete annealing, temperature gradient, or inhomogeneity.
Structural Glass — Flat glass or glass blocks used for structural purposes
Tank — A melting unit, in which the container for molten glass is constructed from refractory blocks; also called 'Tank Furnace'.
Thermal Shock — A sudden variation in temperature as applied to glassware.
Toughened Glass — Glass, the surface of which has been rapidly cooled

from near the softening point, so that a residual compressive stress remains after complete cooling. This increases the thermal endurance and mechanical strength of the glass and tends to make it shatter into smaller and less angular fragments than an ordinary glass when it is subjected to a breaking stress; also called tempered glass.

Transparent — Allowing light rays to be transmitted, without noticeable absorption so as to be distinctly see through.

Vello Process — A process for continuously drawing glass tubing or rod in which glass is fed downward to the draw through an annular orifice to a horizontal draw back.

Weathering — Physical or chemical deterioration of a glass surface caused by exposure to the earth's atmosphere.

Welding Glass — Coloured glass to protect a welder's eyes from injurious radiation.

Window Glass — See 'Sheet Glass'.